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REFERENCE

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

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American Journal of Science

FEBRUARY 1953

THE EFFECTS OF EXTRUSION AND SOME OTHER PROCESSES ON THE MICRO-STRUCTURE OF CLAY

J. H. WEYMOUTH AND W. O. WILLIAMSON

ABSTRACT. The micro-structures of plastically deformed fine-grained kaolinitic clay were studied optically in pyroxylin-backed films peeled from appropriate surfaces of the specimens. Planar parallelism, involving (001) of the aggregated clay-flakes, and linear parallelism revealed by the disposition of rutile and tourmaline prisms, were observable in extruded cylinders. The relations between these types of parallelism and the schlieren produced by using parti-colored clay are discussed. Shear-joints cut across the fabric indicated by the disposition of (001). They contained clay in which the arrangement of (001) allowed the relative movement of the walls of the joints to be deduced. Such deductions were made for extruded cylinders and for slabs subjected to rotational strain in a manner previously employed by Riedel. Attention is directed to analogies between the experimentally produced structures and those seen in naturally deformed rocks.

INTRODUCTION

THE effect of flow on the orientation of clay-particles suspended in water has been investigated optically (Marshall, 1949, pp. 87-88). Popov (1944) has made an optical study of deformation in a clay-water system of greater consistency. Comparable study of deformed plastic clay has been neglected. However, the stripping of pyroxylin-backed films from the smoothed surfaces of appropriate specimens served to demonstrate the orienting effects which processing operations had on the feldspar, quartz and other nonplastic ingredients of ceramic "bodies"; the arrangement of the accompanying clay-flakes was not observed but should tend to conform with the disposition of these ingredients (Williamson, 1941). Later, the same technique was found to be applicable to a fine-grained "ball" clay. The micro-preparations of this clay, although obtained from dried specimens, revealed structures which had clearly been formed by deformation when the clay was still

plastic (Williamson, 1947*a*). Identical methods have been employed in the present investigation to extend the study then begun.

MATERIALS AND METHODS

The English "ball" clay used was not manifestly different from that studied earlier (Williamson, 1947*a*, 1947*b*). Its chemical analysis appears in table 1; mineralogical analysis by X-ray methods showed the presence of kaolinite with smaller amounts of illite and some quartz. The kaolinite and illite could not be differentiated when pyroxylin-backed clay-films were examined with the polarizing microscope; innumerable minute prisms of authigenic rutile and a few grains of quartz were, however, seen (cf. Williamson, 1947*a*). More detailed search should disclose further accessory mineral-species.

The rutile-prisms, although their maximum dimensions were considerably greater than those of the individual clay-particles, lay with a preferred orientation within the aggregates of parallel flakes. The c-axes of the prisms were parallel to the basal planes of the clay-flakes. Surfaces parallel to the basal planes of these flakes are mentioned frequently in later contexts and, for conciseness, are given the symbol (001).

TABLE 1

Analysis of Ball Clay Dried at 110° C.
(Analyst, Miss B. C. Terrell)

SiO_2	56.53	Cl	Tr
Al_2O_3	29.55	F	Tr?
*Fe_2O_3	1.21	SO_3	0.05
MgO	0.27	ZrO_2	Tr.
CaO	0.30	MnO	Tr.
Na_2O	0.21	BaO	0.05
K_2O	1.50	V_2O_5	0.03
H_2O+	8.41	Cr_2O_3	0.01
CO_2	nil	C	0.17
TiO_2	1.51	B_2O_3	Tr.?
P_2O_5	0.05	Total	99.75

*State of oxidation not determined.

The deformed specimens were dried, cut, smoothed and peeled in the manner described (Williamson, 1947*a*) but a new mixture, giving stronger films, was employed. This contained 10 gm. of

pyroxylin dissolved in a solvent consisting of acetone 100 ml., amyl acetate 45 ml., butyl acetate 15 ml., ethyl acetate 15 ml., castor oil 0.75 ml.; additional solvent was added if necessary.

The pyroxylin-films, peeled from the dried specimens, were remarkable for bringing away with them clay-layers resembling in thickness the usual type of petrological micro-section and similarly amenable to study with the polarizing microscope. The specimens contained minute clay-flakes which were usually arranged with their basal pinacoids in common orientation; thus were produced the (001) planes mentioned above. Films stripped from surfaces parallel to (001) should include flakey aggregates of clay-particles. This was true, but films were prepared as readily from surfaces perpendicular to (001). In such films the clay appeared microscopically as massive aggregates, with a fallacious appearance of monocrystallinity, which behaved optically like sections of large kaolinite-crystals cut parallel to the c-axis. In reality, each aggregate was built of minute clay-flakes lying perpendicularly to the surface of the film with their basal pinacoids in approximate parallelism; the mutual boundaries of these flakes were not perceptible. That the aggregates have such a constitution is indicated by table 2 which shows that most individual clay-flakes have maximum dimensions much smaller than the thickness of the stripped film which is commonly not less than 30-40 microns.

TABLE 2

Grain-size Analysis of Clay
(method of Andreasen)

Percentage	weight	less	than	25	micron	equivalent	spherical	diameter	97.0
"	"	"	"	10	"	"	"	"	96.0
"	"	"	"	5	"	"	"	"	90.8
"	"	"	"	2	"	"	"	"	81.1
"	"	"	"	1	"	"	"	"	74.9

The clay-films, still on their pyroxylin-backing, were mounted in Canada balsam in the usual way and then examined with the polarizing microscope. Parallelism of the constituent clay-flakes was observable by noticing the tendency for the field to extinguish in certain positions of the stage and to show maximum illumination at 45° thereto. In kaolinite c approximates to X and directions normal to c to Y or Z; thus orientation in the

micro-preparations was readily deducible by conventional methods and particularly by use of the sensitive tint plate.

THE EFFECTS OF EXTRUSION ON MICRO-STRUCTURE

Introduction.—The extruder was a hollow cylinder of brass, 12.5 mm. in internal diameter, closed at one end by a circular plate which was part of a piston. This piston moved forward by air-pressure and forced the contents of the cylinder through a brass die at the other end. The die commonly employed had a shoulder which presented a tapering surface to the cylindrical reservoir. A circular aperture 6.5 mm. in diameter in the center of this surface led to a cylindrical exit canal, 16 mm. long, co-axial with the reservoir (fig. 1).

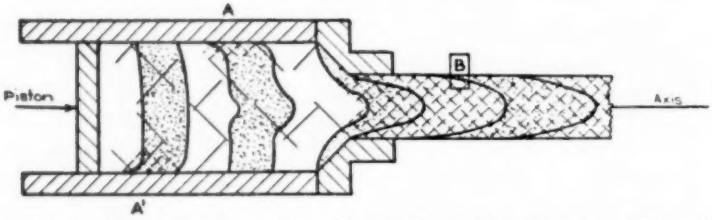

Fig. 1. Diagrammatic section of extruder with alternate white and colored discs in process of extrusion. Diagonal shear-joints are occasional in the reservoir-filling but abundant in the extruded column. The complex system of shear-joints in and near the shoulder of the die is not depicted. Drastic rearrangement of the fabric has occurred at A and A′ where spaces had existed between the reservoir-wall and the edges of the discs. At B is the type of region photographed in plate 2, figure 1.

When the reservoir contained a continuous piece of plastic clay, the pressure from the piston caused a redistribution of the water-content of the filling (Riedel, 1929*a*). This effect was not obvious where the filling was a collection of individual discs as in the experiments to be described.

Movement of the piston was stopped when the contents of the reservoir had been only partly expelled. After the clay had dried in place, the unextruded residue remained attached to the extruded column. Clay-films from appropriate surfaces allowed the fabric of the entire deformed mass to be deduced. Description of this fabric will be attempted under the headings: (1) the unextruded residue; (2) the extruded column; (3) the zone of maximum deformation in which the clay is involved during its approach to and passage through the die.

(1) *The unextruded residue.*—The initial filling consisted of circular discs which had their broad surfaces in contact, their edges against the reservoir-wall, and their axes co-axial with the reservoir. These discs were built of aggregated clay-flakes which had (001) parallel to the broad surfaces. They were made by the process of single-surface casting already described (Williamson, 1947*a*) or by a process of double-surface casting developed subsequently. In some experiments alternate discs were dyed with methylene blue.

Friction between the filling and the reservoir-wall was reduced by an oil-film; however, drag at this wall sufficed to cause the broad surfaces of the discs to become feebly convex in the direction of flow. The original fabric had been slightly re-arranged so that (001) was in approximate parallelism to the newly curved surfaces. A more drastic re-arrangement had occurred at some points against the wall where, in zones up to ca. 0.5 mm. across, (001) was now subparallel, not perpendicular, to the wall-surface (A and A′ in fig. 1). The effect was most marked where small gaps, since filled by plastic flow of the clay, had existed between this surface and the edges of the discs. The appearance, in some unextruded residues, of regularly repeated zones characterized by an orientation differing from that of the general fabric was also indicative of localized deformation; these zones showed where imperfect contacts had once existed between the broad surfaces of adjacent discs.

Ill-defined systems of shear-joints were commonly seen. In planes containing the axis of the unextruded clay-cylinder they appeared as two sets of traces which intersected at about 90° and made angles of ca. 45° with the trace of (001) in the fabric which they traversed. Subsequently, they are termed "diagonal shear-joints." They are considered to follow the curved surfaces of cones or of semi-ellipsoids[1] in the manner deduced below for similar structures in the extruded columns themselves.

In films normal to the shearing-surfaces, the diagonal shear-joints appeared as continuous thin strips of clay with an optically positive elongation subparallel to the length of the strip; thus (001) was oriented in the shearing-planes. It is shown later that (001) commonly lies at a small angle to these planes.

[1] The term "semi-ellipsoid" is used throughout for convenience of description but has no necessary mathematical implications.

The diagonal shear-joints developed during the compression of the reservoir-contents which accompanied extrusion; their formation was assisted by frictional effects at the metal walls, and possibly by the collapse of cavities which had existed in the ill-compacted clay.

(2) *The extruded column.*—The diameter of the dried column was ca. 5.5 mm. The structures revealed by films taken from the surfaces indicated by A, B and C in figure 2 will be considered in order:

A. *A plane containing the axis of the column.*—Extrusion has caused most of the clay-flakes to turn through angles up to 90° so that (001) now tends to be parallel to the axis of the column; the degree of parallelism is intensified towards the curved surface. Along the axis itself, however, are regions wherein the flakes, by maintaining their original disposition, still lie with (001) perpendicular to this axis. Such regions contain

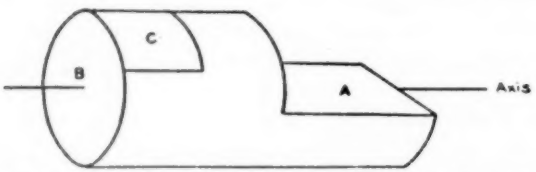

Fig. 2. Extruded cylindrical column. Key diagram to show the surfaces A, B and C from which clay-films were stripped.

residues which have escaped the shearing, involving slip on (001), which occurred during the passage through the die. Laterally they develop into trains of flakes which curve back towards the die-mouth until (001) becomes parallel to the surface of the column (figs. 1, 3). Where the reservoir had been filled with white and blue clay-discs, alternately arranged, the regions of residual orientation were found to be associated with the apices of the semi-ellipsoidal color-bands which appeared in the extruded column; these color-bands or schlieren have their convex sides directed away from the die-mouth. Such color-bands, usually in clay extruded from the "pugmills" of the ceramic industries, have been depicted but details of their microstructures are lacking (Richardson, 1939; Williamson, 1941; Haefeli and Amberg, 1949; cf. Pearson, 1944, fig. 89 for results from extruded metals). When clay-columns from pugmills are

dried, they may show preferred cracking in directions which are potentially those of the schlieren described above; freezing of the columns develops a pattern of ice-films which follows the same directions (Davenport, 1951; Haefeli and Amberg, 1949). Such phenomena prove the existence of systematically arranged planes of weakness. Comparably, the columns of the present experiments developed hair-cracks on drying or contained localized films showing very intense shearing by slip on (001); these cracks and films curved in sympathy with the color-bands and were commonly found at the boundaries between bands of different colors.

The regions of residual orientation, associated with the axis of the column, were discontinuous; they alternated with other regions in which (001) was approximately parallel instead of

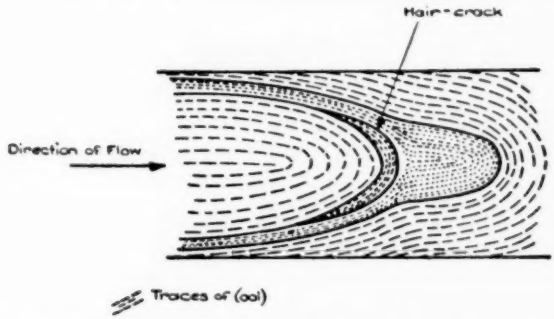

Fig. 3. Diagrammatic axial section of extruded column showing regions of residual orientation. All broken lines represent traces of (001) but dyed clay is indicated by closer shading. In the "nose" of dyed clay a region of residual orientation is bounded on one side by a hair-crack. This region, on the other side, trespasses into the white clay. Difficulties in drawing have led to certain traces of (001) being represented as making acute angles with, instead of being parallel to, the traces of the curved surface of the column.

perpendicular to the axis. Residual orientation was particularly evident where, prior to extrusion, there had been contacts between the faces of contiguous clay-discs. Adjacent discs showed differences in ease of deformation, associated with differences in water-content, and the location of regions of residual orientation depended on this fact as is illustrated in plate 1, figure 1. Here the more deformable blue clay is seen to have plunged forward as "noses" ahead of the less deformable white clay. In these noses (001) is largely reoriented parallel to the axis

of the column. On the concave side of each nose is a region of residual orientation which continues into the convex part of the adjacent arc of white clay (fig. 3). In some examples the region extends completely across the arc and trespasses into the nose of blue clay which follows. The average water-contents of discs used to produce a specimen showing slightly less differential deformation of the color-bands than is visible in plate 1, figure 1 were: white discs 27 per cent, blue discs 29 per cent.

Diagonal shear-joints were obvious; they were filled with clay which had (001) approximately parallel to the shearing-planes (plate 1, fig. 2). Such shear-joints were not relics of those seen in the reservoir-filling because the fabric which they traversed had been produced from that of the filling by a process of nonaffine deformation. Their traces were straight lines or lines which curved slightly in sympathy with the curvature of the color-bands. The rearrangement of the clay-flakes during extrusion was increasingly drastic from the axis to the outside of the column (fig. 3). Thus the formation of those shear-joints which are now visible necessarily post-dated most of this rearrangement. This surmise was confirmed by examining regions where the joints crossed the color-bands at large angles, i.e., near the exterior of the column. The boundaries between the blue and the white bands were repeatedly faulted by minute movements along the shearing-surfaces which intersected them (plate 2, fig. 1).

It remains to consider the form in space of the shear-joints. In microscopical preparations stripped from planes containing the axes of cylinders the shear-joints appeared as two sets of straight or slightly curved traces intersecting at about 90° and making angles of approximately 45° with the surfaces of the cylinders. The traces maintained this disposition irrespective of how the plane of section was rotated about the axis of the cylinder. Thus they represent the curved surfaces of cones or semi-ellipsoids having axes coincident with the axis of the cylinder. Two sets of such cones or semi-ellipsoids must be postulated: the apices of one set are directed away from the die-mouth and of the other set towards it.

B. *A plane perpendicular to the axis of the column.*—When the film stripped from such a circular section was examined with the sensitive tint plate, it split up into four equal sectors which

PLATE 1

Fig. 1. Photograph of axial section through reservoir-filling, zone of maximum deformation, and extruded column (fig. 1). "Noses" of the more deformable dyed clay are visible.

Fig. 2. Photomicrograph of shear-joints in axial section of extruded column. One of the two sets of joints is more perceptible. (Crossed Nicols X 60.)

Fig. 1. Photomicrograph showing faulting of schlieren by shear-joints in an area such as B in figure 1. (Crossed Nicols X 120.) Some of the field is in extinction. The boundary between the white and the dyed clay is indicated by the broken lines joining A to B. The faulting made visible by the arrangement of these lines was associated with movement along two sets of shear-joints of which one, not in extinction, is perceptible.

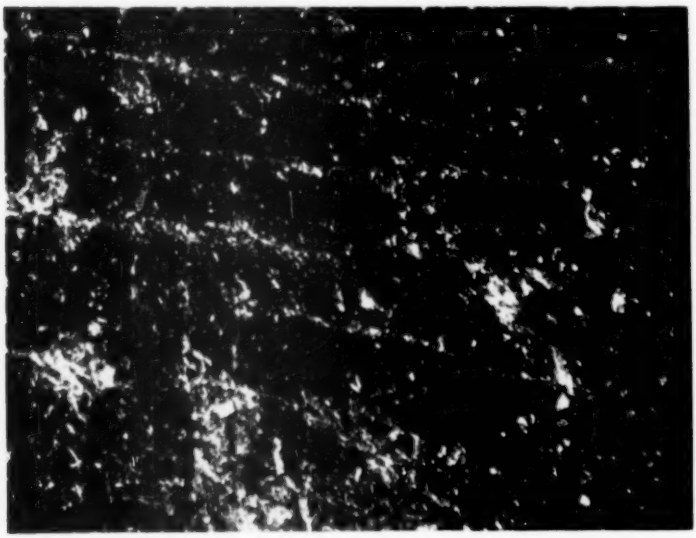

Fig. 2. Photomicrograph of shear-joints produced in Riedel's experiment, cf. fig. 7. The line of junction of the boards is parallel to the length of the photograph (Crossed Nicols X 63.)

were colored either blue or orange; pairs of opposite sectors showed the same color. Towards the center of the column the sectors were less distinct and the blue and orange colors became more irregular in their distribution. The general arrangement of the colors indicated a fabric in which (001) of the clay-aggregates followed the curved surface of the column but, away from this surface, took up other positions.

Circular sections across columns containing schlieren exhibited alternate rings of blue and white clay concentrically arranged about the axis of the column and increasing in thickness as the axis was approached.

The shear-joints were not discernible. This accords with their postulated form in space (see above) which suggests that here they would be represented by circular traces concentric with the point of emergence of the axis of the column. The disposition of (001), being identical with that in the surrounding fabric, would not permit these traces to be distinguished optically.

C. *The curved surface of the column or a parallel surface close beneath it.*—Many flakey clay-aggregates appeared. The extent of their surfaces, contrasted with the much smaller dimensions suggested by the grain-size analysis (table 2), showed that they were built of minute units not distinguishable microscopically. Their irregular extinction, more obvious in the larger aggregates, may be symptomatic of their composite nature. The flakey aggregates tended to lie with the maximum diameters of their surfaces parallel to the length of the column; the optical sign of this elongation was positive. Similar aggregates, described previously, were thought to have been synthesized during processes of plastic deformation (Williamson, 1947*a*). They can be formed also by casting (op. cit.) and thus were identifiable in films stripped from planes parallel to the broad surfaces of the discs used for filling the reservoir (see above). Their optical behavior could be explained in part by the presence of minute flakes which had their basal pinacoids in parallel arrangement and, in addition, a tendency for their a- and b-axes to be in common alignment. Montmorillonite is known to form aggregates with such a structure (Hauser and Le Beau, 1938; 1939; Hauser, 1951, personal communication). The optically positive elongation along the major diameters of the surfaces of the present aggregates suggests the further supposition that

the b-axes of the constituent crystalline units have a preferred orientation in this direction. It is hoped to study these polysynthetic flakes in more detail.

The diagonal shear-joints were not certainly identified, probably because the angles which they made with the surfaces studied were too acute.

The existence of minute prisms of authigenic rutile, arranged preferentially on (001) of the clay-aggregates, was mentioned earlier. The prisms, although they maintained this arrangement during the deformation of the clay, had now acquired a distinct parallelism aligned with the axis of the extruded column; the existence of a second lineation in (001) at right angles to the first, although feasible, was not obvious on mere inspection (Cloos, 1946, p. 12). The lineation marked by the rutile-prisms was followed also by infrequent prisms of blue-green tourmaline. This tourmaline, although prismatic, was flattened in (001) of the containing aggregate; it appeared to be authigenic. The most robust crystal noticed presented a prismatic surface 0.30 x 0.05 mm.; most of the rutile-prisms were, however, below 0.14 mm. long and had length: breadth ratios in excess of 10:1. The linear parallelism of the rutile and tourmaline was effected by slip on (001) in their clay-mineral host.

The descriptions given under A, B and C show that the structure of the column was essentially similar to that deduced for a cylinder of electrical porcelain, extruded from a pugmill, by noting the disposition of the nonplastic ingredients alone (Williamson, 1941, fig. 8; cf. fig. 2 of the present communication).

(3) *The zone of maximum deformation.*—The reservoir was filled with discs of blue and of white clay, alternately arranged, and extrusion from it was arrested when only about half of the contents had been expelled. A film was stripped from a plane which contained the axis of the reservoir-cylinder and of the extruded column. Because these two axes were aligned, the film corresponded to a plane of symmetry cutting the zone of extreme deformation in which the clay was involved during its approach to and passage through the die. The color-bands, which hitherto were arched only slightly in the direction of flow, were seen to have moved forward more rapidly in the axial, as against the lateral regions, in the vicinity of the die (cf. Pearson, 1944, fig. 89 for a comparable occurrence in the

extrusion of tin). Thus were initiated the semi-ellipsoidal color-bands found in the extruded column. The clay-flakes continued to lie with (001) parallel to the boundaries between the color-bands, both in the zone of maximum deformation and in the extruded column of which this zone is the precursor. This arrangement is analogous to that seen in flow-banded igneous rocks where tabular crystals lie with their major surfaces in the planes of the schlieren.

In the zone of maximum deformation (001) rotated through angles up to 90°. This rotation did not represent a revolution of undeformed clay-aggregates on their own axes but was the result of progressive slip on (001). The angle of 90° was attained only where the zone of intense shearing, adjacent to the tapering shoulders of the die, contributed to the border-zone of the clay-stream entering the cylindrical canal that led to the exit; this border-zone ultimately formed the outside of the extruded specimen, i.e., that region where (001) was most nearly parallel to the axis of the column. On the contrary, axially lying structural elements underwent a minimum of deformation (Pearson, 1944, p. 101) and hence could survive in the column as the regions of residual orientation already described.

The structures produced where the die had square instead of tapering shoulders differed from those described in only one important particular. The shoulders contained stagnant regions demarcated from the mobile clay by narrow belts in which intense shearing had aligned (001) in general accord with the surface of separation. In the dried clay this surface was often followed by actual hair-cracks. Similar stagnant regions developed in clay subjected to extrusion from Riedel's apparatus (Riedel, 1929*a*, plate 8); they have been depicted also for extruded metals (Pearson, 1944).

In the stagnant regions produced by the present experiments the original orientation was still to be found, i.e., (001) tended to be perpendicular to the axis of the reservoir-cylinder. The fabric was, however, crossed by a meshwork of diagonal shear-joints filled with the usual positively elongated clay-strips. These joints resulted from compression, which may have been particularly intense before the increasing pressure from the piston caused the adjacent clay to separate from the potentially stagnant regions and commence its flow through the die.

In specimens partially extruded through the various dies, the shear-joints, which had appeared only sporadically in the contents of the reservoir, became abundant in the zone of maximum deformation. These joints formed a pattern resembling that figured by van Iterson for the trajectories of maximum shear-stress in comparable circumstances (van Iterson, 1947, fig. 51; Salmang, 1951, fig. 22).

The intersecting sets of diagonal shear-joints, which were so obvious in the extruded column, became well developed only as the clay entered the straight canal leading to the exit orifice (fig. 1). Thus they were formed, as has been deduced already, after the more drastic rearrangement of the fabric had ceased. Similar joints were produced by extruding clay from the same reservoir but through other dies; these dies had tapering shoulders and cylindrical exit canals which were 9.5 mm. or 3.5 mm. in diameter.

The presence of such joints implied that the issuing clay-column had been subjected to lateral compression and axial extension. The validity of this hypothesis was proved by study

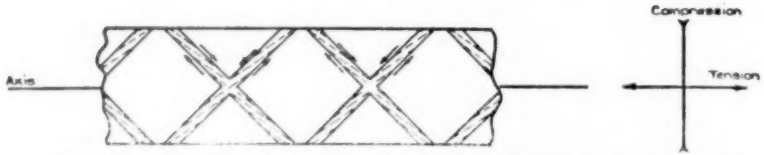

Fig. 4. Shear-joints in axial section of extruded cylinder. Traces of (001) marked. Diagrammatic and not to scale.

of the clay-strips which filled the joints. These commonly had extinction-directions which made acute angles of up to 15° with the traces of the shearing-surfaces; these directions were shown optically to be the traces of (001). The disposition of the acute angles with reference to the shearing-surfaces was compatible with the arrangement of (001) shown diagrammatically in figure 4. This figure may be compared with that given by Hills (1943, fig. 18).

The shear-joints in certain dykes, although their form in space is different, are similar in origin to the present examples if they were formed by lateral compression, accompanied by extension of the dyke along its course (Balk, 1937, fig. 15). However, there is evidence that in some instances differential movement of the dyke-walls is involved (Blyth, 1950).

DIAGONAL SHEAR-JOINTS PRODUCED BY OTHER TYPES OF DEFORMATION

Introduction.—Such shear-joints may be defined as those which cut across the fabric of the clay, as revealed by the parallel disposition of (001), and are themselves filled with clay-layers having (001) subparallel to the shearing-surfaces. Their presence in extruded clay led naturally to the reinvestigation of certain types of deformation described elsewhere to see if they had been overlooked. In addition, some novel types of deformation were attempted.

Slapped discs.—The preparation and fabric of these have been recorded (Williamson, 1947*a*). Further attention was directed to films stripped from planes parallel to the circular faces of the discs and limited by the edges. This was to discover if the markings on the edges, previously classified as cross-joints resulting from tension, were actually shear-joints. The evidence obtained suggested that the former designation was correct and was strengthened by the results of a new experiment. The edges of the discs were slotted radially and further spreading of the clay promoted by continuing the fabrication-process. The slots became V-notches pointing towards the centers of the discs. Thus tangential tension was operating in the manner previously assumed; indeed, the stress-conditions in a peripheral sector were like those shown diagrammatically by Cloos (1946, p. 28, fig. 7a).

Compressed discs (Williamson, 1947*a*).—The two sets of peripheral shear-joints were found to be open or to be filled with the typical oriented clay-layers. A few of the open joints were walled with oriented clay; here progressive movement had split the previously formed clay-filling.

Rolled rods.—The preparation of these, with a brief note on their micro-structure, has already been mentioned (Williamson, 1947*b*). The fabric, when examined in greater detail, resembled that stated by Knopf and Ingerson (1938, p. 151) to develop from rotational rolling. As was to be expected, it was not traversed by diagonal shear-joints. Certain surface-markings could, however, be equated with the ac cracks produced, according to these authorities, by tensile strain in a direction transverse to the rolling movement.

Repeated alternations of axial tension and compression were applied manually to the rods, as in the diagnosis of "backlash" (Macey, 1948; Williamson, 1947*b*). The clay sheared along systems of surfaces inclined to the axis in the manner mentioned by the two investigators cited. Microscopical study revealed that the shearing had produced typical diagonal joints, of which some were open but others were filled with the usual oriented clay-layers.

Flexed slabs.—These were of interest because they showed a measurable extension caused by slip along shearing-surfaces. Rectangular slabs, approximately 5 x 2.5 cm. by 0.5 cm. thick, were made by a process of double-surface casting which tended

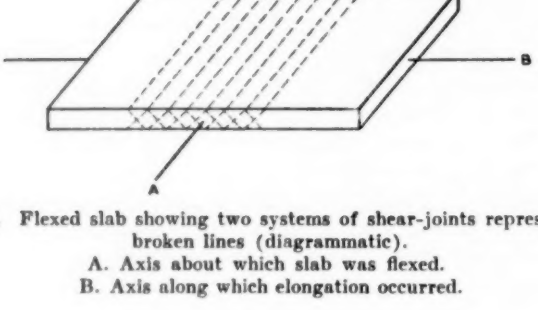

Fig. 5. Flexed slab showing two systems of shear-joints represented by broken lines (diagrammatic).
A. Axis about which slab was flexed.
B. Axis along which elongation occurred.

to orient (001) parallel to their rectangular surfaces. They were flexed onto a circularly curved surface 5.7 cm. in diameter and at once gently flattened. They were then flexed in the opposite direction and again flattened. This procedure constituted one cycle of deformation. The flexing was about an axis perpendicular to the length of the slab (fig. 5). After five cycles of deformation two systems of shearing-surfaces had become obvious: these intersected along lines parallel to the axis mentioned. Slip on these surfaces produced elongations of 3%-5% parallel to the lengths of the slabs.

Microscopically the shear-joints were seen to be unusually wide and to be filled with oriented clay-layers. Some joint-fillings were so robust that they appeared as ramifying streaks, in which (001) was approximately parallel to the walls and was marked

by rutile-prisms which had maintained their tendency to lie in this plane. The streaks enclosed tiny fragments of the matrix in which the general fabric of the slab was still preserved.

Rotationally strained slabs.—Various investigators have caused shear-joints to form in plastic clay while they were elucidating, by analogy, certain natural deformation-mechanisms which have affected rocks; the micro-structures of the clay in or near these shear-joints have not been recorded. To remedy this deficiency, an experiment made by Riedel (1929*b*) was repeated in a modified form. A slab of clay ca. 6.5 x 4.0 cm. by 2-3 mm. thick was cast in a manner which oriented (001) parallel to the two major faces of the slab. The slab was placed symmetrically across the junction between two horizontal wooden boards (fig. 6). One board was then displaced for a short distance in a direction parallel to its line of junction with its neighbor (cf. Hills, 1943, figs. 21 and 88). This movement produced a rotational strain in the clay-slab adherent to the boards. The results of this strain were investigated by allowing the slab to dry and examining a clay-film stripped from a horizontal surface about 1 mm. above the line of junction of the boards. Two sets of vertical shear-joints were visible (plate 2, fig. 2). The major set was arranged en echelon at an angle

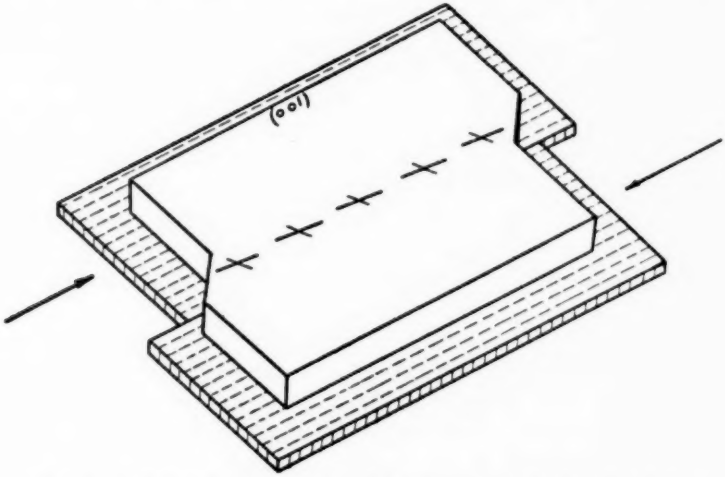

Fig. 6. Rotational strain of clay-slab lying across the junction between two boards, with shear-joints indicated (diagrammatic).

of a few degrees to the line of junction of the boards. The less well-developed set was at angles of 80°-90° to the first. The clay-strips in both sets of joints extinguished at angles of up to 15° with reference to the traces of the shearing-surfaces; this extinction-direction was, as usual, the trace of (001). The arrangement of the extinction-angles was compatible with the dispositions of (001) indicated diagrammatically in figure 7: this figure may be compared with those given by Turner (1948, fig. 39a and b).

THE ORIENTING MECHANISM IN DEFORMED CLAY

If the nomenclature of petrofabric analysis is adopted, the specimens described may be classified as: (1) non-tectonites which showed depositional orientation marked by parallelism of (001), i.e., cast discs or slabs; (2) tectonites, i.e., specimens deformed by extrusion or other processes.

The oriented fabrics produced, for example, by extrusion resulted from componental movements which were essentially not the external rotation of the clay-aggregates but the slip of their constituent flakes along (001). The existence of such an effect was implicit in earlier descriptions of the fabric of "slapped" discs (Williamson, 1947*a*, p. 650 ff.). The effect is reminiscent of the mechanism postulated by Sander, in contrast to Schmidt, to explain the rearrangement of mica during the natural deformation of rocks (Knopf and Ingerson, 1938, pp. 166-167; Turner, 1948, pp. 270-274). The slip in clay-aggregates is, however, not along glide planes in a crystal-lattice but occurs within the water-layers which separate the opposing (001) surfaces (Williamson, 1951). However, certain dried montmorillonitic films slip on (001), in a manner more directly analogous to that postulated for mica by Sander, when they are hammered in a special way (Hauser and Le Beau, 1939).

The fillings of the diagonal shear-joints had a fabric which truncated that of the host except in a few examples where there was a curving transition between the orientations of (001) in the two fabrics. The extreme fineness of most of the clay-particles doubtless enhanced their ability to slip into and reorient themselves along shear-joints, even where the movement along such joints had been very slight; thus was produced

a clay-strip which commonly appeared to be demarcated from the differently oriented matrix.

The joint-fillings, as seen in sections normal to the shearing-surfaces, showed an extinction which, although commonly sharp, was rarely parallel to the traces of these surfaces; the extinction-direction, which was the trace of (001), made a small angle with them. The implication is that differential movement of the walls of the shear-joints, although not usually adequate to align (001) parallel to these walls, sufficed to leave (001) at a small angle to them. A similar structure is seen in the slip-zones of the Melibokus granite which contain inclined but parallel biotite-flakes (Knopf and Ingerson, 1938, plate 4, fig. 1); mimetic crystallization of biotite appears to be involved in contrast to the actual slip of clay-flakes recorded in the present experiments. It is interesting to find that, according to Allen

Fig. 7. Traces of (001) in shear-joints of Riedel's experiment. AA' line of junction of the boards. (Diagrammatic, cf. fig. 6 and plate 2, fig. 2).

(1945), clay-minerals themselves were oriented in certain fissure-fillings by processes of mimetic crystallization.

The structure of dykes described by Blyth (1950) also invites comparison; these dykes, although intruded into unsheared country rocks, showed vertical shearing-surfaces parallel or at a small angle to their walls. This phenomenon was ascribed to relative movement of the bounding walls in a direction parallel to their course. The orientation of (001) in the clay joint-fillings might, at first sight, be assumed to correspond to that of the shearing-surfaces in the dykes, because of the similar formative mechanism. Comparison of figures 4 and 7 with various figures given by Blyth shows, however, that the acute angle made by (001) with the direction of movement of the adjacent bounding wall of clay points in a direction opposite to that of the corresponding acute angle made by the shearing-surfaces and the direction of movement of the associated dyke-wall; this apparent anomaly appears to have been explained by Blyth himself (1950, p. 415, esp. fig. 11).

The production of systems of shear-joints in plastic clay could be symptomatic of a lattice-like structure which is, however, imperfect. On this hypothesis, clay-particles separated by water-films tend to take up positions in a force network such that potential energy is reduced to a minimum. Many particles fail to secure such positions and hence slip is more readily initiated in their vicinity. Macey, in particular, has elaborated such ideas (Williamson, 1951, esp. p. 18 and refs. cit.).

In conclusion it may be recalled that van Iterson (1947) has emphasized the inapplicability of the term "slip-planes," i.e., the "shear-joints" of the present context, to certain structural discontinuities which accompany plastic flow. However, slip-planes were undoubtedly produced during our experiments (cf. plate 2, fig. 1).

SUMMARY

A fine-grained kaolinitic clay was deformed plastically and the resulting micro-structures investigated by a technique in which coherent films were stripped from smoothed clay-surfaces. Particular attention was given to fabrics produced by extrusion-processes in which a cylinder was forced through a die to form a second cylinder narrower than but coaxial with the first. The original cylinder was built of contiguous discs in which were clay-aggregates having (001) arranged at right angles to its axis. In the extruded cylinder (001) had turned through angles up to 90° from its original position but this was not caused by external rotation of the clay-aggregates. It resulted from cumulative slip along (001) in which the interstitial water between the clay-flakes was involved. The use of an alternation of stained and unstained clay-discs caused semi-ellipsoidal color-bands to develop in the resulting extruded cylinder. The disposition of (001) was co-planar with the boundaries of these schlieren. In the outer layers of the cylinder was seen a linear parallelism to the axis; this was marked by minute prisms of rutile and tourmaline which lay on (001) of the clay-minerals and thus in the planes of the schlieren.

Diagonal shear-joints crossed the fabric of the extruded cylinder. They contained clay-layers having (001) at a small acute angle to the shearing-surfaces. The arrangement of the acute angles was compatible with the formation of the cylinder by a process of lateral compression and axial elongation. Simi-

lar shear-joints were produced by a variety of other deformation-processes. Differential movement of the walls of the joints produced the structures found in the clay-layer between these walls; comparison is made with similar structures in dykes.

The formation of sets of shear-joints in plastic clay accords with the hypothesis that the clay-particles, separated by water, are arranged as a lattice in which many fail to achieve positions of minimum potential energy; hence are found regions in which shearing is more readily initiated.

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SHORELINES OF THE GLACIAL GREAT LAKES IN COOK COUNTY, MINNESOTA*

ROBERT P. SHARP

ABSTRACT. Lateral tracing of shoreline features of the Glacial Great Lakes provides a better basis for recognition and correlation of ancient water planes than heretofore available in Cook County, Minnesota. In addition to the shore features of Lake Duluth, Lake Algonquin, and Lake Nipissing, previously identified in this area, five lower Algonquin shorelines, resembling those of Georgian Bay in Lake Huron, are distinguished and provisionally assigned local names. Possibilities appear good that a relation can be established between the lowest of these, the Deronda, and the Minong beaches of Isle Royale, thus ultimately providing a possible means of relating lower Algonquin levels in the Superior and Huron basins.

The degree of tilt displayed by various shorelines in Cook County is consistently lower than previously stated. The uplift in Cook County may have been more uniform than in other parts of the Superior basin indicating differential warping in the Earth's crust during the postglacial recoil rather than uniform tilting as a rigid plate over a wide area.

INTRODUCTION

SHORELINE features of ancient lakes in the Superior basin have been studied along the Minnesota coast most extensively by Lawson (1893) and Leverett (1929, pp. 57-71), and most recently in the Duluth area by Schwartz (1949, pp. 70-73). Lawson's field data were supplemented, analyzed, or interpreted by Upham (1894, pp. 56-66), Grant (1899, pp. 338-343), Taylor (1897), and Martin (1911, pp. 443-448) among others. These earlier workers, Schwartz excepted, dealt largely with data obtained along widely spaced profiles extending inland from the present shore.

In Cook County the lateral extent of shoreline features has been mapped wherever possible. This procedure was greatly facilitated by air photos, an advantage not available during earlier studies. Lateral tracing provides more certain identification of shoreline features as such, leads to recognition of distinguishing characteristics of particular shorelines, and results in more certain correlation of discontinuous features along an ancient water plane than can be obtained solely from transverse profiles.

The following shorelines are distinguished in Cook County, from highest to lowest: Lake Duluth; sub-Duluth; highest

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Lake Algonquin; a group of lower Algonquin shorelines locally named Lutsen, Marais, Tofte, Kodonce, and Deronda; and finally Lake Nipissing; and sub-Nipissing (fig. 12). Identification of the Duluth, Algonquin and Nipissing shorelines was earlier made by Leverett (1929, pp. 57-71).

This work constitutes part of a geological study of Cook County made largely by Frank F. Grout under auspices of the Minnesota Geological Survey. Appreciation is expressed for the aid and advice of Grout, George M. Schwartz, and Herbert E. Wright of the University of Minnesota. George M. Stanley kindly reviewed the manuscript and offered numerous suggestions based on his long experience with similar features in the

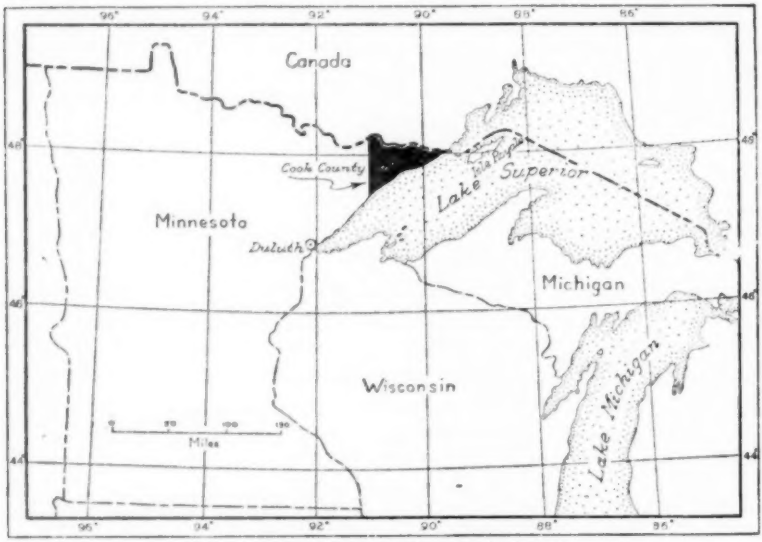

Fig. 1. Location map for Cook County.

Great Lakes region. Field work on the Pleistocene features of Cook County covered a period of approximately 3½ months during the summers of 1946 and 1947.

PHYSICAL SETTING

Cook is the northeasternmost county (fig. 1) of Minnesota (47° 55′ N., 90° 30′ W.). Its triangular shape is determined by the eastward convergence and eventual junction of the

Canadian border with the north shore of Lake Superior. Cook County borders Lake Superior for a distance of 80 miles as measured along a straight line bearing N. 62° E. The actual shoreline is considerably longer owing to irregularities (plate 1, fig. 1).

Over much of this distance the land attains elevations up to 1000 feet above the lake within a few miles inland. The hard rocks and steep slopes of this coast did not generally favor as strong development nor as good preservation of shoreline forms as in other areas.

SHORELINE FEATURES

Wave-cut cliffs.—This is the most abundant form along the ancient water planes. Most cliffs are 20 to 30 feet high, a few attain 50 feet, and some are laterally continuous for miles as, for example, along the Nipissing water plane east of Grand Marais. A flattish tread mantled by gravel or shingle lies below the cliffs in many places. The highest and sharpest cliffs are cut in platy rhyolite and red clay till. Those formed in diabase and basalt are mostly lower and less continuous.

Beach ridges.—Abandoned beach ridges are easily identified and provide convincing evidence of former lake levels. Unfortunately, they are limited largely to lower shorelines, the Deronda, Nipissing, and sub-Nipissing. This arises in part from a flattening of the coastal slopes at the lower levels.

Most Cook County beach ridges are composed of fine pebbly gravel, but some consist of well-worn boulders averaging 1 foot in diameter (plate 2, fig. 2). Beach ridges are usually larger, more numerous, and coarser near the mouths of streams because of debris supplied therefrom. Heights of a few feet are average, 5 to 8 feet is not unusual, and one ridge at Deronda Bay attains 9 feet. Individual ridges have widths of 5 to 20 feet, and multiple assemblages are 75 to 100 feet wide. Favorable conditions of a gently sloping shore, abundant loose debris, and strong wave action prevailed at Deronda Bay where 20 pebbly ridges are found within the first 50 feet, vertically, above Lake Superior (fig. 10). Good beach ridges were also formed near Grand Portage, at Wauswaugoning and Horseshoe bays, and at Paradise Beach.

Beach ridges may be built in a relatively short time during storms. Although providing good evidence of shoreline activity,

they do not necessarily indicate a long-continued stability of the water plane.

Lake terraces.—Many of the so-called lake terraces in Cook County (Schwartz, 1925, pp. 80-82) are actually gravel-mantled dip slopes on Keweenawan lavas and intrusives. Bona-fide terraces are seen above and below the Nipissing cliff east of Grand Marais, at the base of a prominent cliff on the Kodonce shoreline 110 feet above lake level near Tofte, and at Thomasville in the southwest corner of the county.

Lake deposits.—For the most part sub-aqueous deposits indicate only that the area has been submerged and are not particularly useful in locating shorelines. This is especially true of the red clays laid down by Lake Duluth and its successors along much of the Cook County coast. Materials of near-shore origin such as thin accumulations of sand and gravel; interlayered sand, silt and clay beds dipping lakeward; and abandoned deltas, especially at the mouths of Temperance, Cascade, and Brule rivers and several smaller streams indicate approximate minimum elevations for former water planes.

Miscellaneous features and relations.—Leverett (1929, pp. 61-64) appears to have used the upper limit of "wave-washed" slopes as an indicator of the highest shoreline in some areas. To his trained and discerning eye this may have been a reliable criterion, but in Cook County bare rock slopes are numerous far above the level of the Glacial Great Lakes and this criterion was not applicable.

A series of flattish treads backed by steep risers can be recognized in the profiles of many ridges and slopes bordering Lake Superior. Good examples of stairlike steps are seen along Caribou Lake road, McFarland Lake road, a road on the east edge of sec. 25, T. 60 N., R. 3 W., and along the trails leading to lookouts on Mt. Leveaux and Mt. Josephine. Lawson (1893, pp. 242, 252-253, 280) interprets many such features as the marks of ancient shorelines, and some of the risers do indeed have the aspects of wave-cut cliffs. If the associated treads are mantled by shore gravels and if the form has some lateral extent, a shoreline origin seems likely. However, many of the topographic breaks appear to be the product of subaerial erosion controlled by structures within the gently dipping Keweenawan volcanics. They are not considered reliable shore-

line markers unless discordant with bedrock structure and confirmed by some independent evidence.

Reliability and accuracy of shoreline features as indicators of water planes.—Cliffs are the most accurate indicator of water plane elevations in this area, but even they are not ideal. The wave-cut notch at the cliff base is usually buried by debris, and the exact level of the water line cannot be determined more closely than several feet. Furthermore, the base of a continuous cliff does not necessarily have a uniform elevation, for on

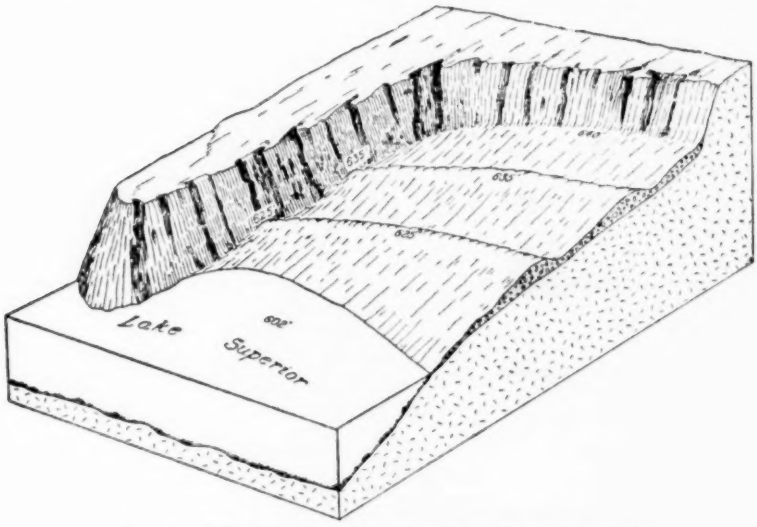

Fig. 2. Diagrammatic sketch showing different elevations at base of cliff.

exposed headlands it is usually lower than in re-entrants. Along the Nipissing shoreline near Kodonce Creek the cliff base on a projecting headland is 10 feet lower than in an adjacent bight. This may be due in part to lithologic relations, as the headland is composed of platy rhyolite and the bight is in red clay till. More likely, it is due to the fact that the base of a cliff can be progressively lowered by wave erosion as the water level falls, provided the offshore water is deep (Stanley, 1937, p. 1683). As the water level fell, in the example cited, the waves built beach ridges in the re-entrant while they continued to cut the headland cliff (fig. 2).

Beach ridges are usually built by storms to heights a few feet above mean water level. At Deronda Bay a storm ridge on the present beach rises 7 feet above water level, and at Horseshoe Bay the crest of a similar boulder ridge is 11 feet above water level. Lawson (1893, p. 231) reports modern beach ridges along the north shore of Lake Superior 9 to 14 feet above water level. These figures are probably extreme, but since some ridges are of subaqueous origin (Stanley, 1936, p. 1936), a 10-foot range in elevation is possible for beach ridges along a water plane. Deane (1950, p. 79) reaches a similar conclusion.

Thus, elevations based on the most reliable shoreline features in Cook County may be as much as 10 feet off the level of the water plane, although most departures are probably not this great. Nonetheless, it is obvious that separation of shore features and conclusions as to degree of shoreline tilting cannot be based on differences of only a few feet.

METHODS OF STUDY

Elevations were measured to the crests of beach ridges and to the bases of wave-cut cliffs. Near bench marks or close to the present shore, measurements were by hand leveling. Other elevations, including the majority, were determined by barometer and are considered accurate within 10 feet at the higher levels and within 2 or 3 feet at the lower shorelines. This modest accuracy was obtained by repeated measurements to the same feature, often on different days, by frequent reference to the level of Lake Superior, and by recourse to numerous bench marks established in 1935 by the Coast and Geodetic Survey, two of which are located exactly on ancient shorelines. Evaluation of the various shoreline features is attempted in the following tabulations (tables 1 to 10). More data are included in these tables than are shown in the maps (figs. 4-11).

LAKE DULUTH

The large body of water impounded in the Superior basin as the late Wisconsin Superior lobe receded east-northeast was first termed "Western Superior Glacial Lake" (Upham, 1894, p. 54) but subsequently became known as Lake Duluth. Its outlet was southward to the Mississippi by way of St. Croix River.

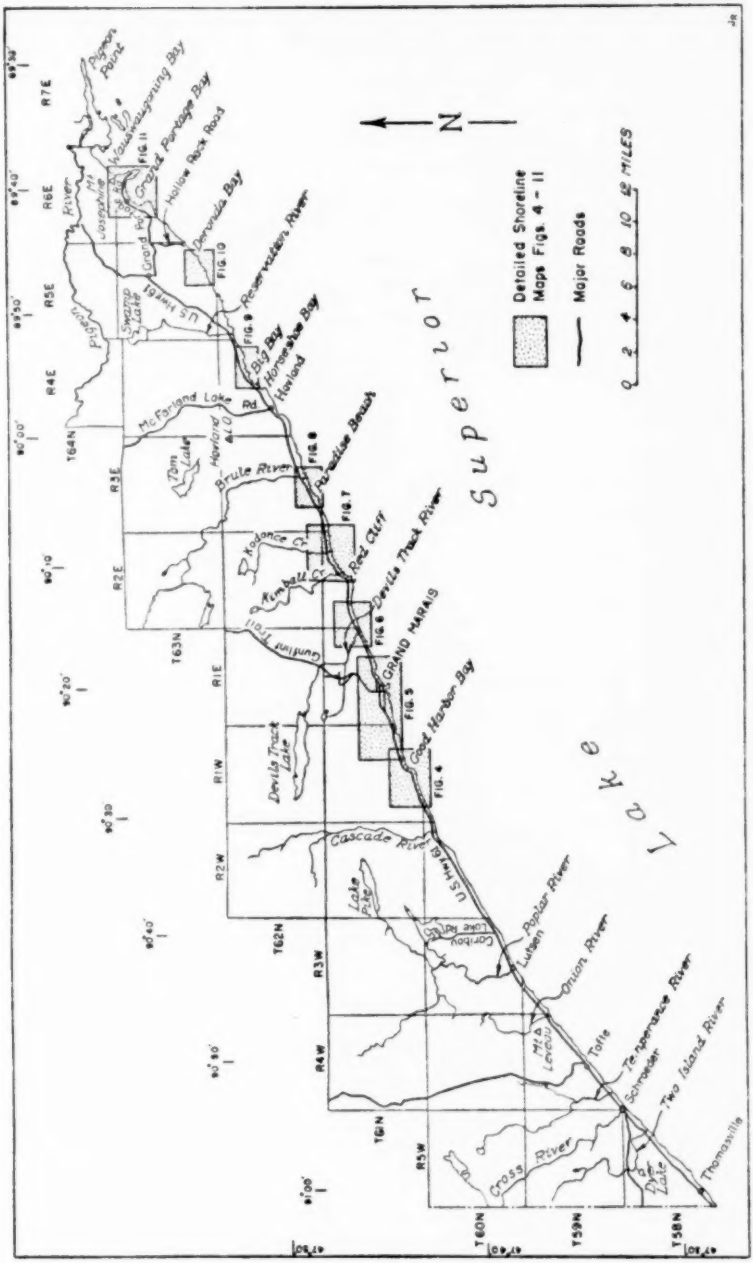

Fig. 3. Locations of detailed shoreline maps.

In its westernmost part, Lake Duluth is represented by 3 strong beaches, separated by intervals of 25 feet, and possibly by a fourth beach, 25 feet higher (Leverett, 1929, p. 59). The upper levels in this series supposedly do not extend into Cook County, because the outlet was lowered by erosion while the lake expanded eastward after the receding ice front. Leverett (1929, p. 59) records the following Lake Duluth levels in Cook County: in the southwestern corner at 1191, 1175, and 1126 feet above sea level;[1] on Poplar River at 1224 feet; north of Grand Marais at 1275, 1250, and 1206 to 1209 feet; and northwest of Hovland at 1300 feet. During the present study the following shoreline features attributed to Lake Duluth were identified (table 1).

TABLE 1

Shoreline Features of Lake Duluth in Cook County

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Mt. Leveaux	Narrow tread at base of steep rock slope, good lateral extent	1225	fair
Caribou Lake road	Bedrock riser	1250	poor
North of Good Harbor Bay (fig. 4)	Wave-cut cliff 30 feet high and gravel-mantled tread	1270	good
	Wave-cut cliff, 50 feet high, and tread	1250	good
Northwest of Grand Marais (fig. 5)	Strong cliff with gravel at base	1255-1260	good
	Strong double cliff with narrow intervening terrace	1258 and 1270	good
	Double cliff, weaker	1240 and 1280	fair
North of Grand Marais (fig. 5)	Weak cliff	1280-1290	poor
	Weak tread and riser	1270	fair
Red Cliff - Kodonce Creek area (fig. 7)	Topographic break with gravel, good lateral extent	1270	poor
Mt. Josephine	Gravel bar	1265	poor

[1] Elevation of the water level in Lake Superior is 602 feet.

Shoreline features of Lake Duluth are most prominent north of Good Harbor Bay and Grand Marais (figs. 4 and 5) where a wave-cut cliff up to 50 feet high can be traced with minor interruptions for 4.5 miles. In places, it is a double cliff with a narrow intervening tread (plate 1, fig. 2). Aside from a gravel bar at Mt. Josephine, the Lake Duluth shores in Cook County are marked solely by cliffs or risers fronted by narrow gravel-mantled treads.

The most reliable altitudes obtained for Lake Duluth water planes are near Grand Marais and Good Harbor Bay. These range from 1240 to 1270 feet above sea level, roughly 640 to

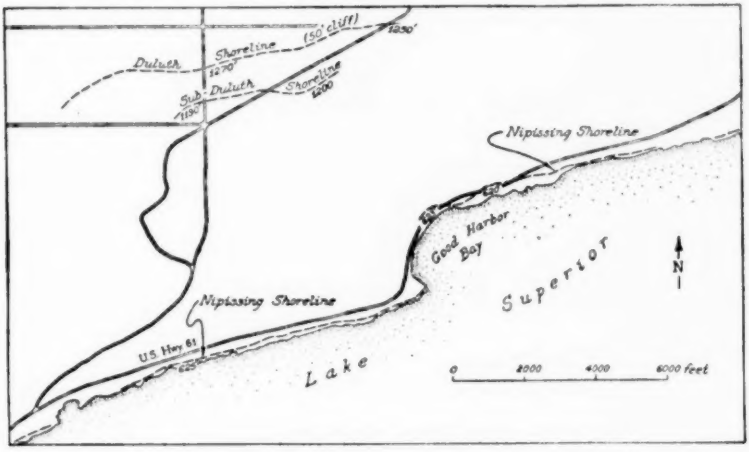

Fig. 4. Shoreline features in Good Harbor Bay area.

670 feet above Lake Superior, and the close agreement with some of the figures cited by Leverett for this locality is gratifying. However, no traces could be found of the Lake Duluth shorelines reported by Leverett in the southwest part of the county, at Poplar River, or northwest of Hovland.

SUB-DULUTH PHASE

With further eastward recession of the Superior lobe, a lower outlet was opened on the flanks of the Huron Mountains in Marquette County, Michigan. This permitted waters of the Superior basin to drain into Lake Chicago. At this time a large independent lake, Algonquin I, occupied the Huron basin, and

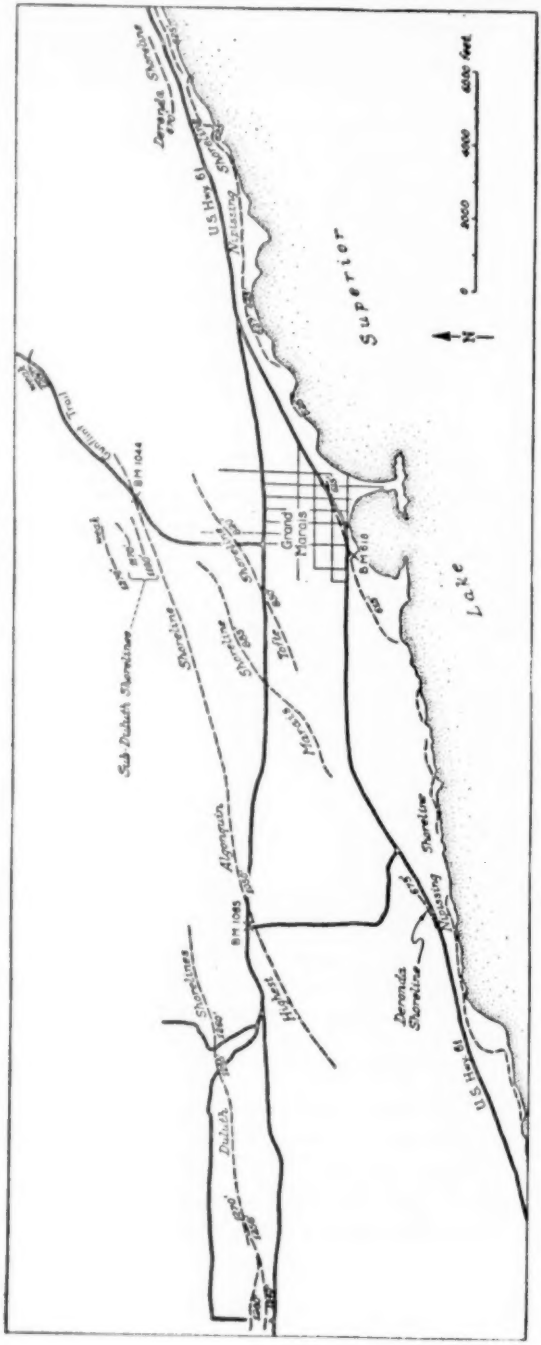

Fig. 5. Shoreline features in Grand Marais area.

subsequently waters in the Superior basin became part of Lake Algonquin II.[2]

Shoreline features in Cook County between the lowest level attributed to Lake Duluth and the highest Algonquin shore are herein designated sub-Duluth. Leverett (1929, p. 63) recognized that the drop from the Duluth to the Algonquin level occurred intermittently as successively lower outlets were developed between the Huron Mountains and the receding ice lobe. The nature and elevation of features assigned to the sub-Duluth phase are summarized in table 2. Among these features, the wave-cut cliff north of Good Harbor Bay, 1190 to 1200 feet above sea level or 590 to 600 feet above Lake Superior, is the strongest.

TABLE 2

Features of the Sub-Duluth Phase

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Schroeder	Topographic break with gravel, good lateral extent	1160	fair
Mt. Leveaux	Modest tread and step	1165	poor
	Steep rock cliff with well-formed tread	1130	fair
Caribou Lake road	Sand deposit	1200	poor
Good Harbor Bay (fig. 4)	Wave-cut cliff, prominent, good lateral extent	1190-1200	good
Grand Marais	Rock cliff, 40-50 feet high with narrow bouldery tread	1170	fair
	Gravel deposit	1130	poor
	Rock cliff, 10-15 feet high with narrow bouldery tread	1100	fair
Devils Track River (fig. 6)	Cliff	1175	fair
Hovland	Riser	1210	poor
	Topographic break with gravel	1100	poor
Mt. Josephine	Gravel bar	1205	fair

[2] Much has been written about the history of the Glacial Great Lakes, but a brief up-to-date account with pertinent references to the literature is provided by Flint (1947, pp. 254-262).

LAKE ALGONQUIN

The Superior basin first became part of Lake Algonquin during the Algonquin II stage (Flint, 1947, p. 256) when the Superior, Michigan, and Huron basins were integrated into a single huge lake with an outlet via Trent Valley, Ontario (Leverett and Taylor, 1915, pp. 412-413). Subsequently, post-glacial uplift on the north raised the Trent outlet and diverted some of the overflow southward into the St. Clair River past Detroit and into the Des Plaines-Illinois channel at Chicago. During this transitional stage the "Algonquin beach"[3] was cut. Continued uplift eventually diverted the entire overflow into the southern outlets. This initiated Algonquin III, during which so-called "upper" Algonquin shorelines in the Huron basin were formed. Further ice recession eventually opened a series of lower outlets across highlands east of Georgian Bay, and the water planes of the Algonquin IV stage were established. The data tabulated below (table 3) pertain to the highest Lake Algonquin shore features recognized in Cook County.

TABLE 3

Highest Shoreline Features of Lake Algonquin in Cook County

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Grand Marais (fig. 5)	Rock cliff, 10 feet high, with gravel at base	1044-1050	good
Devils Track River (fig. 6)	Extensive break with gravel	1045-1055	good
	Extensive break with gravel	1020-1030	good
Red Cliff - Kodonce Creek area (fig. 7)	Extensive break	1030	fair
Mt. Josephine (fig. 11)	Extensive cliff and tread	1058	good

Highest Lake Algonquin features are best seen near Grand Marais and Devils Track River where low cliffs and risers with good lateral extent have been mapped (figs. 5 and 6), at elevations of 1020 to 1055 feet. The close agreement between the

[3] The term "Algonquin beach" is used for the shore features developed during this transitional stage (letter, G. M. Stanley, March 5, 1949). For a corresponding recommendation see Deane (1950, p. 43).

1042 given by Leverett and the 1043.604 feet of a Coast and Geodetic Survey bench mark set on an Algonquin shoreline north of Grand Marais is noteworthy.

It is possible that the highest Algonquin shorelines in Cook County were cut during the Algonquin III stage, Algonquin II being too transitional or perhaps standing at a lower level. However, this cannot be demonstrated on the basis of local data. If radiocarbon dating of the Mankato climax is correct (Flint and Deevey, 1951, pp. 261-263), the entire history of the Glacial Great Lakes probably took place in the last 10,000 years. Lake Algonquin III existed about half way through this period, 4,930 ± 260 years ago (Flint, 1951, p. 889).

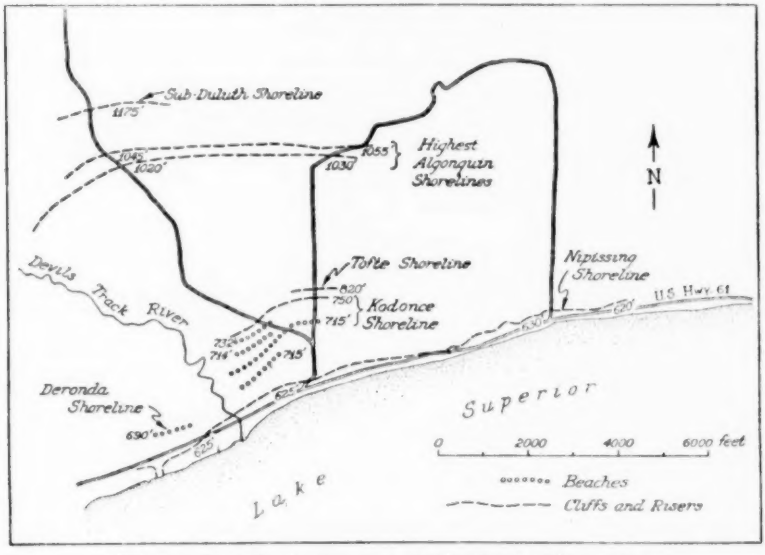

Fig. 6. Shoreline features in Devils Track River area.

LOWER ALGONQUIN SHORELINES

Shore features are scattered over the 400-foot interval between the highest Algonquin shores and the Nipissing level in Cook County. Some of these features were probably earlier attributed to the Battlefield and Fort Brady groups (Leverett and Taylor, 1915, pp. 433, 436), which, according to Leverett (1929, p. 68) are well represented along the north shore of Lake Superior, but he cites no localities and gives no elevations.

Detailed studies by Stanley (1936, 1937) in Georgian Bay of Lake Huron established four lower Algonquin shorelines between the "upper" Algonquin level and Lake Nipissing, and Deane (1950, p. 43) finds a corresponding situation in the Lake Simcoe District, Ontario. At Lake Huron these shorelines all display approximately the same tilt as the "upper" Algonquin water planes and were presumably formed, not by uplift, but by opening of successively lower outlets across the highlands between Georgian Bay and Lake Ontario. Since the Battlefield and Fort Brady beaches were supposedly abandoned because of uplift and should, therefore, not be parallel with the "upper" Algonquin shores, Stanley (1936, p. 1955) suggests that use of these names be discontinued for the present. He has given local names to the lower Algonquin shorelines in Georgian Bay.

In keeping with this procedure the shore features between the highest Algonquin levels and Lake Nipissing in Cook County, here arranged in five groups, are given the following local names from highest to lowest: Lutsen, Marais, Tofte, Kodonce, and Deronda. This is wholly provisional and is

TABLE 4
Features of the Lutsen Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Schroeder	Topographic break with gravel, good linear extent	950	fair
Tofte	Gravel deposit	975	poor
Mt. Leveaux	Topographic break with gravel	950	fair
Onion River to Lutsen	Beach ridge	1000	fair
	Beach ridge	970-975	fair to good
Caribou Lake road	Sand and gravel	980, 985	poor
Grand Portage	Gravel deposit	970	poor
Mt. Josephine	Tread and cliff	965	fair
	Tread and cliff	958	fair

adopted primarily as an aid in presentation of data. Exact correlations are not yet possible, but it seems likely that these shores are of the Algonquin IV stage.

Lutsen shoreline.—The highest of the lower Algonquin levels is named from the resort center of Lutsen. The relative paucity and weakness of the Lutsen shore features (fig. 12) suggest that the water plane was not long stabilized at this level. The most reliable mean elevation is between 975 and 985 feet, or about 375 and 385 feet above Lake Superior. Table 4 summarizes pertinent data.

Marais shoreline.—This shoreline is named from a low but extensive gravel-fronted cliff just north of Grand Marais (fig. 5). Other features of this water plane are to be seen along the Caribou Lake road and on Mt. Josephine as shown in table 5. Mean elevation is 885 feet, or 283 feet above Lake Superior.

TABLE 5

Features of the Marais Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Mt. Leveaux	Topographic breaks with gravel	910, 895, 845	poor
Caribou Lake road	Extensive topographic break with gravel	900-910	fair
	Topographic break with gravel	870-875	fair
Grand Marais (fig. 5)	Extensive low cliff with gravel, well developed	885	good
West of Brule River	Cliff, weak	920	poor
	Topographic break with gravel	840	poor
Grand Portage	Gravel accumulation	845	poor
Mt. Josephine	Cliff and tread	880	fair

Tofte shoreline.—This shoreline is named from two beach ridges at Gervais airport north of Tofte. Good features can also

be seen near Grand Marais (fig. 5) at 820 to 830 feet elevation, roughly 200 to 230 feet above Lake Superior. Pertinent data are presented in table 6.

TABLE 6

Features of the Tofte Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Temperance River	3 beaches	770-780	poor to fair
Tofte	2 beaches	792, 800	fair to good
	Break with sand	770	poor
Mt. Leveaux	Cliff with good tread, good linear extent	780	fair to good
Onion River to Lutsen	Gravel beach	795-800	fair
	Strong cliff	815	good
Caribou Lake road	Break with gravel	805	fair
	Break with sand	775	fair
Grand Marais (fig. 5)	Extensive riser with tread and gravel	820-830	good
Devils Track River (fig. 6)	Cliff	820-830	fair
Red Cliff - Kodonce Creek	Gravel deposit	835	poor
	Topographic break	820	poor
West of Brule River	Topographic break with gravel	800	poor to fair
Brule River mouth	Gravel deposit	815	poor
Mt. Josephine	Cliff and tread	800	fair

Kodonce shoreline.—An extensive riser at 745 feet elevation near Kodonce Creek (fig. 7) identifies this shoreline. It is also represented by a prominent cliff and wide terrace at the village of Tofte, and by features in many other parts of Cook County (fig. 12). The elevation of 712 to 715 feet at Tofte, 110 to 113 feet above Lake Superior, appears the most reliable. Data are summarized in table 7.

TABLE 7
Features of the Kodonce Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Thomasville to Two Island River	Weak cliff, upper limit of gravel	700-718	poor to fair
Schroeder	Topographic break with gravel	755	poor
Temperance River	Cliff	715	fair
Tofte	Strong cliff and terrace	712-715	good
Onion River to Lutsen	Local cliff	715	fair
Caribou Lake road	Riser	737	poor
Good Harbor Bay	Gravel deposits	715, 730	poor
Grand Marais	Gravel deposits	700, 735, 750	poor
Devils Track River (fig. 6)	Four beaches and one riser	715-750	fair to good
Red Cliff to Kodonce Creek (fig. 7)	Extensive cliff	745	good
West of Brule River	Gravel deposit	725	poor
Brule River Mouth	Gravel deposit	730	poor
Hollow Rock road	Two boulder beaches	703, 710	fair
Grand Portage area (fig. 11)	Beaches	725, 742, 750	fair
	Gravel deposit	750	poor

Deronda shoreline.—A large beach ridge at Deronda Bay (fig. 10) identifies this shoreline. The same level is marked by beaches, local cliffs, and gravel accumulations in many other parts of the county. Elevations between 670 and 690 feet, roughly 70 to 90 feet above Lake Superior, appear most representative as shown in table 8.

TABLE 8

Features of the Deronda Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Thomasville	Gravel on terrace	675-685	fair
	Broad beach ridge	657	fair
Dyer Lake area	Beach and cliff line	685	fair
	Gravels on terrace	665	poor
Two Island River	Cliff and beach ridge	640	fair
Schroeder area	Beaches and cliffs	650-685	fair to good

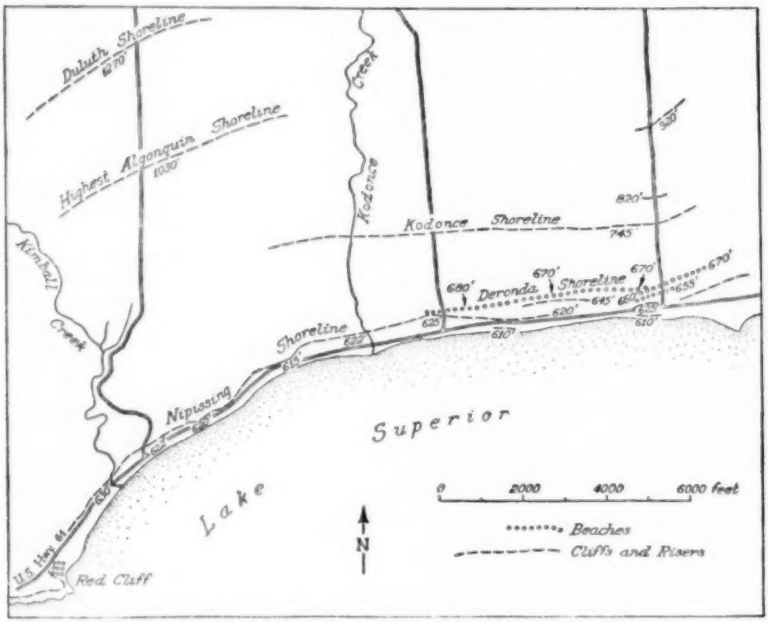

Fig. 7. Shoreline features in Red Cliff-Kodonce Creek area.

TABLE 8 (Cont.)

Features of the Deronda Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Temperance River mouth	Cliff	650-660	fair
Onion River	Cliff and gravel	675	poor
Lutsen to Caribou Lake road	Terrace	675	fair
	Gravel deposit	690	poor
Caribou Lake road	Topographic breaks	680, 685	poor
	Topographic break with gravel	658	fair
East of Caribou Lake road	Cliff	650	fair
Cascade River	Beach gravels and broad beach ridge	690	fair
Good Harbor Bay	Gravel deposit	685	poor
Grand Marais (fig. 5)	Cliff, with gravel tread	670-675	fair
East of Grand Marais (fig. 5)	Gravels and cliff	670-690	poor
Devils Track River (fig. 6)	Topographic break with gravel	670-685	poor
	Gravel beach	690	fair
Red Cliff-Kodonce Creek (fig. 7)	Break	690	poor
	Strong beach and break	670-680	good
	Two beaches	655, 660-670	fair
West of Brule River	Breaks with gravel	670-690	poor
Brule River mouth (fig. 8)	Cliff	665-670	fair
Hovland	Gravel deposit	690	poor
Horseshoe Bay	Gravel deposit	675	poor
Big Bay area (fig. 9)	Boulder beach ridge	675-680	good
Reservation River	Gravel Deposits	672, 697	poor
Deronda Bay (fig. 10)	Beach ridge, extensive	665	good
Grand Portage (fig. 11)	Beach ridges	680 672 652-670	good
Mt. Josephine	Cliff and tread	690	poor
Wauswaugoning Bay	Boulder beach ridge	679	good

A possible relation between the Deronda shoreline and Stanley's (1941) Minong beaches on Isle Royale warrants attention. Stanley has kindly furnished the following unpublished information. Elevation of the highest of a continuous series of Minong beaches at the southwest end of Isle Royale is 685 feet, and their angle of tilt is 2.6 feet per mile along a line bearing N. 22° E.

From these data, elevations of the highest Minong beach at Wauswaugoning Bay, Grand Portage, and Deronda Bay in Cook County are calculated as 677, 675, 660 feet respectively.

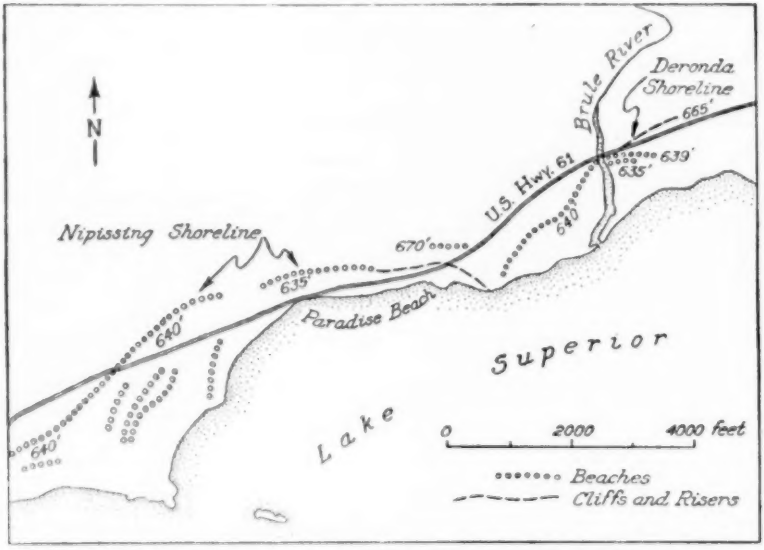

Fig. 8. Shoreline features in Brule River-Paradise Beach area.

Actual elevations of the highest Deronda shoreline at these spots are 679, 680, and 665. This close agreement, and the fact that the Deronda shore displays a series of lower levels at Grand Portage and at Deronda Bay resembling the lower Minong beaches on Isle Royale, leads Stanley to the conclusion[4] that Minong beaches are represented among the data in Cook County as far west as Deronda Bay.

Although correlation of the Minong and Deronda shores in eastern Cook County seems a good possibility, some reserva-

[4] Personal communication.

PLATE 1

Fig. 1. Lake Superior Coast at Grand Portage Bay, looking west-southwest from Mt. Josephine.

Fig. 2. Double cliff (A and B) and intervening terrace cut in red clay till along Lake Duluth shoreline northwest of Grand Marais (NW 1/4 sec. 23, T. 61 N., R. 1 W.). Cliff bases at 1270 and 1258 feet above sea level.

Fig. 1. Lake Nipissing cliff 30 feet high cut in red clay till east of Kodonce Creek (NW 1/4 sec. 1, T. 61 N., R. 2 E.). Base of cliff at 625 feet altitude, beach ridges in foreground.

Fig. 2. Bouldery Lake Nipissing beach ridge 40 feet above Lake Superior (642 feet altitude) at Horseshoe Bay.

tions are held because correlation west of Deronda Bay is less certain. For example, at Big Bay (fig. 9) the level identified as Deronda is marked by a prominent boulder beach at 680 feet. The highest Minong beach should have here an elevation of 647 feet if the angle of tilt established by Stanley remains constant. Even if elevation of the Deronda beach at Big Bay is adjusted for a maximum observational error of 10 feet, it is still far above the calculated height of the Minong water plane. Farther west, Deronda shore features are also consistently too high for correlation with Minong beaches. This difference might

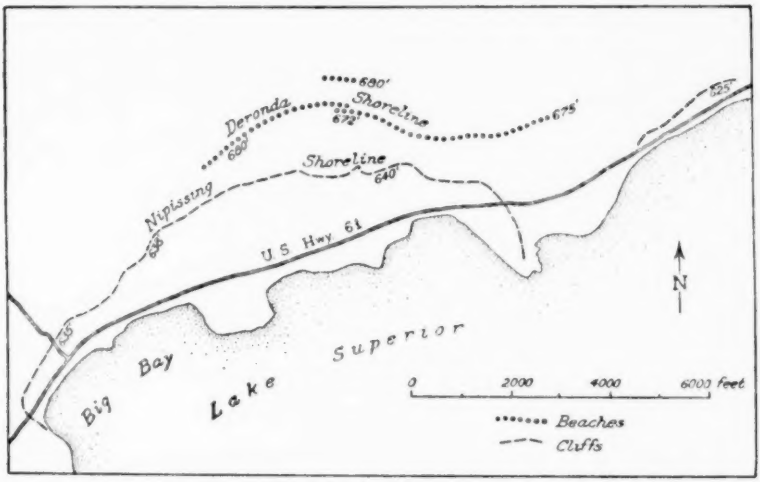

Fig. 9. Shoreline features in Big Bay area.

be resolved if the angle of tilt in Cook County were not as steep as on Isle Royale, and, as subsequently shown, the inclination of other shorelines in Cook County supports this possibility.

Summary statement on lower Algonquin shores.—In this work, a strong feature of considerable lateral extent was considered a necessary requisite for recognition of a specific water plane, and it is felt that someone else using the same field data on lower Algonquin shore features would arrive at reasonably similar interpretations. Of the shorelines identified, the Lutsen and Marais are the weakest (fig. 12), although each is marked by local features of considerable strength.

Identification of five lower Algonquin shorelines here as compared to four in Georgian Bay (Stanley, 1936, 1937) need not be especially significant. If a specific relation between the Deronda and Minong beaches can be firmly established, a means of correlating Cook County and Georgian Bay water planes

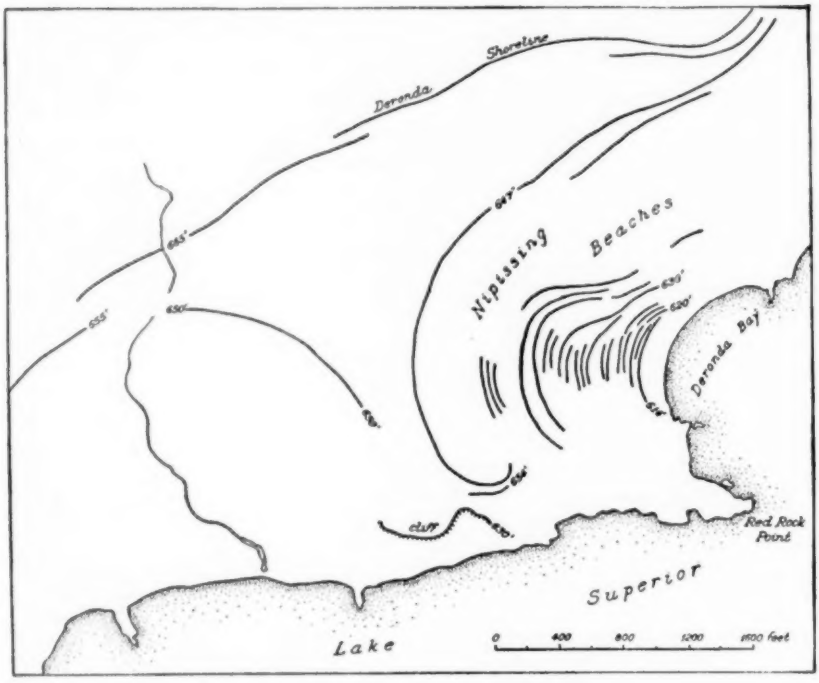

Fig. 10. Shoreline features at Deronda Bay.

may be provided, although Stanley (1936, p. 1956) is not yet certain of the relation between Minong beaches and the shorelines at Georgian Bay.

Identification of these Cook County shores as lower Algonquin, presumably Algonquin IV, is less certain than in Georgian Bay, for here it is not possible to demonstrate a conformity of tilt between upper and lower Algonquin shores or a discordance between them and the Nipissing water planes as in the Georgian Bay area (Stanley, 1937, p. 1678).

NIPISSING GREAT LAKES

In Cook County the Nipissing shore is marked principally by a wave-cut cliff, 15 to 30 feet high, with its base 15 to 35 feet above Lake Superior. This cliff is especially prominent from Grand Marais eastward to Brule River (plate 2, fig. 1). Beach ridges are also numerous along the Nipissing level at Deronda, Grand Portage, Wauswaugoning, and Horseshoe bays and at Paradise Beach. Table 9 summarizes pertinent data.

TABLE 9

Shoreline Features of Lake Nipissing

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Thomasville	Cliff	615-620	good
Dyer Lake to Two Island River	Cliff	617-620	fair to good
Schroeder area	Cliff	630-635	fair
	Boulder beach	640	fair
Temperance River	Cliff	615, 630	fair to good
Tofte	Cliff	620	fair to poor
Onion River to Lutsen	Cliff and terrace	615-620	good
Lutsen to Caribou Lake road	Cliff and terrace	615-620	good
Caribou Lake road and east	Cliff and terrace	615-625	good
Cascade River and west	Cliff and terrace	620-630	fair to good
	Beach ridge	640	poor
Good Harbor Bay	Cliff	615-626	good to fair
Grand Marais (fig. 5)	Cliff and terrace	615	fair
East of Grand Marais (fig. 5)	Cliff and terrace	620-627	good
Devils Track River (fig. 6)	Cliff and terrace	620-630	good
Red Cliff-Kodonce Creek (fig. 7)	Cliff and terrace	615-630	good

TABLE 9 (Cont.)
Shoreline Features of Lake Nipissing

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
West of Brule River	Beach ridges	630-640	good
	Cliff	640	fair
Brule River (fig. 8)	Beach ridges, cliff	635-639	good
East of Brule River	Beach ridges	625-636	good
	Beach ridges	615-630	fair
Hovland	Cliff	620-627	fair to poor
Horseshoe Bay	Beach ridge	640	good
Big Bay (fig. 9)	Cliff	635-640	good
	Cliff	625	fair
Reservation River	Cliff	630	fair
Deronda Bay (fig. 10)	Cliff	630	fair
	Beach ridges	614-630	good
	Beach ridges	647-650	good
Hollow Rock road	Cliff	625	fair
	Boulder beach ridge	650	fair
Grand Portage (fig. 11)	Cliff	630-640	good
	Beach ridge	638-640	good
Wauswaugoning Bay	Beach ridge	646	good

In Cook County the Nipissing shoreline, 615 to 640 feet above sea level, is by far the most clearly marked of the ancient water planes. This may be due partly to initial strength of the features, but it must also reflect their slight geological antiquity of 3,656 ± 640 years as determined by radiocarbon dating of early Nipissing peat from the west end of Lake Superior (Flint and Deevey, 1951, p. 284). This dating is not far from Antevs' (1939, pp. 718-720) earlier estimate of 4000 to 6000 years but much less than Merrill's (1936, p. 43) 16,000 years.

It has been argued (Martin, 1932, p. 436) that the Nipissing cliffs are higher than those along the present shore of Lake Superior, and, therefore, indicate a longer period of wave cutting. In many parts of Cook County the modern cliffs are actually equal or superior to the Nipissing cliff. Local relations

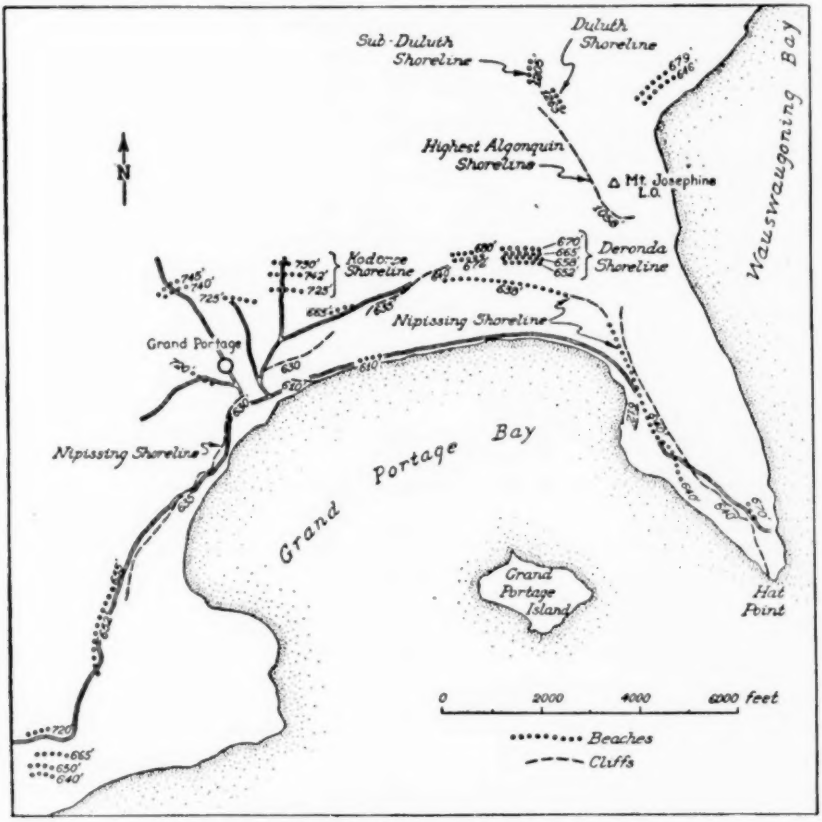

Fig. 11. Shoreline features at Grand Portage Bay.

of rock hardness, exposure, and coastal configuration seem to have as much to do with cliff height and form as any other factors.

SUB-NIPISSING PHASE

A little below the strong Nipissing shore features in Cook County are a few small cliffs and beaches marking the position

of a lower water plane, 10 to 12 feet above the level of Lake Superior. These features are designated sub-Nipissing.

At Deronda Bay (fig. 10) a succession of beach ridges extends from the Nipissing to the sub-Nipissing level suggesting a gradual transition between them. However, cliffs along the sub-Nipissing level indicate that the water plane paused here an appreciable time. In the eastern part of the Superior basin, Taylor (1895*a*, p. 166; 1895*b*, p. 312) recognized a shoreline approximately 50 feet below the Nipissing which he initially named the Sault and subsequently correlated with the Algoma of Lake Huron (Leverett and Taylor, 1915, p. 465). If the same separation between Nipissing and Sault levels is maintained into the western part of Lake Superior, the Sault would be below water level in Cook County. Hence, the sub-Nipissing level probably does not correspond to the Sault. Table 10 summarizes the sub-Nipissing shoreline data.

TABLE 10

Features of the Sub-Nipissing Shoreline

Location (from SW. to NE.; see fig. 3)	Feature	Elevation (in feet above sea level)	Rating
Red Cliff to Kodonce Creek (fig. 7)	Cliff	610	good
Horseshoe Bay	Boulder beach ridge	611	good (age questionable).
Deronda Bay (fig. 10)	Beach ridge	614	good
Grand Portage (fig. 11)	Cliff	610	fair
	Beach ridge	612	fair

TILTING OF SHORELINES

Earlier studies over wide areas by many workers have established that shorelines of the Glacial Great Lakes are tilted by relative uplift in the north and northeast. Cook County shorelines have been less steeply tilted by this uplift than heretofore supposed.

The Nipissing shore furnishes the most abundant and reliable data for calculation of tilt. The gradual rise of Nipissing fea-

tures in a northeasterly direction is too consistent to be due to errors in measurements. Altitudes at the base of the Nipissing cliff are for the most part 615 to 620 feet in southwestern and 630 to 640 feet in northeastern Cook County. This indicates a

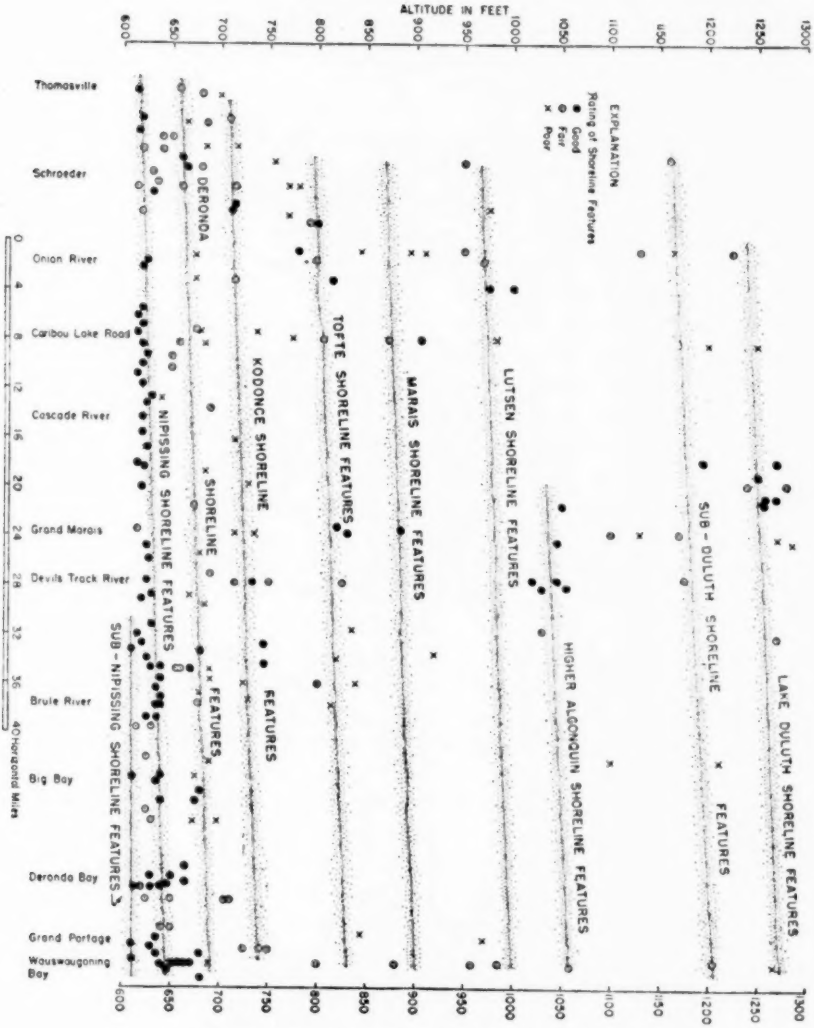

Fig. 12. Profile plots of shoreline features in Cook County. Inclinations of shorelines are approximate.

Fig. 13. Possible angles of tilt for Lake Duluth, highest Lake Algonquin, and Lake Nipissing shorelines.

tilt of about 0.25 feet per mile along a line bearing N. 62° E., roughly parallel to the present shore. A median line through a profile plot of all Nipissing shore features has a somewhat steeper inclination, about 0.33 feet per mile (line F, fig. 13). If these inclinations are resolved into the direction of supposed maximum tilt, N. 30° E. (Leverett, 1929, p. 61), they amount respectively to 0.29 and 0.39 feet per mile. This is distinctly less than the 0.58 feet per mile commonly cited for this area (Taylor, 1895*b*, p. 307; Martin, 1911, p. 449) and the 0.47 feet per mile calculated from Leverett's map (1929, p. 70, fig. 10). A tilt of 0.36 feet per mile on a map by Taylor (Leverett and Taylor, 1915, p. 461, fig. 9) is in closer agreement.

Data from the various lower Algonquin shorelines in Cook County confirm the general direction of tilt but permit such a wide variety of interpretations that no reliable measure of the inclination is possible. Features of the highest Algonquin water plane, although relatively few, are strong and the altitudes are reliable. In profile plot they suggest a mean tilt of about 0.51 feet per mile (line D, fig. 13) or an extreme of 1.19 feet per mile if the lowest features in the west are correlated with the highest in the east (line E, fig. 13). If resolved into the direction of maximum tilt, N. 30° E., these amount to 0.62 and 1.42 feet per mile respectively. Again both the median and the extreme figures are considerably less than the tilt of nearly 2 feet per mile reported by Leverett (1929, p. 68) for highest Algonquin features between the north and south shores of Lake Superior.

In the Good Harbor-Grand Marais area, the Lake Duluth shoreline features extend over a vertical interval of 40 to 50 feet. However, in all other parts of Cook County evidence of only one Lake Duluth level has been found, and its position within the 40 to 50 feet vertical interval cannot usually be determined. This makes calculations of tilt on Lake Duluth shorelines unsatisfactory. A median line through a profile plot of all Lake Duluth shoreline features has a tilt of 0.98 feet per mile along a line bearing N. 63° E. (line A, fig. 13), or 1.18 feet per mile in the N. 30° E. direction. This is far below the 3 feet per mile cited for the highest Lake Duluth level (Leverett, 1929, p. 62). Even if one were to assume that the shore feature at Mt. Leveaux belongs to the lowest and that at Mt. Josephine to the highest Lake Duluth shoreline (line C,

fig. 13), the tilt would be only 1.55 feet per mile, or 1.85 feet per mile in the N. 30° E. direction, still considerably below Leverett's maximum figure. Furthermore, a line drawn through the lowest Lake Duluth features at Mt. Leveaux, Grand Marais, and Mt. Josephine (line B, fig. 13) has a tilt of 0.69 feet per mile, or 0.83 feet per mile in the N. 30° E. direction, which is less than the 1.13 feet per mile given by Leverett (1929, pp. 61-62) for the lowest Lake Duluth shore in Cook County.

The fact that the highest and lowest Lake Duluth shore features show a vertical separation of about 50 feet both at the west end of Lake Superior (Leverett, 1929, p. 59; Schwartz, 1949, p. 72) and in Cook County, 100 miles farther east, throws suspicion on Leverett's postulate of a strong differential tilt between the uppermost and lowermost Lake Duluth shores.

The data gathered in this study consistently indicate lower degrees of tilt than heretofore reported in Cook County. Since the earlier data were sparse and scattered and could be confirmed only in a few instances, it seems likely that Leverett's conclusions were based in some degree on generalizations arising from his work in other areas. Likewise, many of Lawson's (1893, pp. 284-285) observations could not be confirmed, and the basis for his conclusions, that the intervals between shorelines are constant and that no differential tilt exists, appear unreliable.

The tilt of these shorelines is supposedly caused by recoil of a broad area depressed by the continental ice sheet. There is every reason to expect that the Earth's crust will respond to such an uplift by differential warping rather than by uniform tilting as a rigid plate. Detailed studies of shorelines along the extensive north coast on Lake Superior in United States and Canada might well provide a measure of the differences in response of the Earth's crust to this recoil.

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THE PETROLOGY OF THE CARY AND VALDERS TILLS OF NORTHEASTERN WISCONSIN

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ABSTRACT. The Cary and Valders tills in northeastern Wisconsin are described mineralogically and various grain size accumulation curves are reported. The Valders till in this area is shown to be finer textured and more calcareous than the earlier Cary till. The heavy mineral assemblages of the two tills, however, are essentially identical. The name glacial Lake Keweenaw is here proposed for the glacial lake held in the Lake Superior basin by the Cary ice. The Valders till is thought to represent the deposits of glacial Lake Chicago which were removed and redeposited by the Valders ice. The red color is believed to have been imparted by these lake sediments and hence to the later Valders till by the transfer of fine red clastics from glacial Lake Keweenaw to Lake Chicago prior to the advance of the Valders ice.

INTRODUCTION

General Statement

THE Middle and Late Wisconsin stadials are represented in northeastern Wisconsin by the features and deposits ascribed to the Cary and less extensive Valders ice advances. The interstadial is known at the forest bed near Two Creeks, Manitowoc County, Wisconsin, and has been reported from other localities in the Fox River Valley (see fig. 1).

The glacial geology and stratigraphy of eastern Wisconsin has been published by Alden (1918) and Thwaites (1943). Thwaites and Bertrand (1951) are currently extending the mapping through the Door Peninsula in the northeastern part of the state. The interstadial forest beds at Two Creeks have been described by Wilson (1932, 1936) and dated by radiocarbon (Libby, 1952). No concerted attempt, however, has been made to establish the mineralogic and sedimentary characteristics of the Cary and Valders tills from this area. Such a study is reported in this paper.

Methods of Study

Samples numbered C1-3 and V1-2 were collected by Professor F. T. Thwaites while engaged in field work in northeastern Wisconsin (fig. 1). Samples numbered C4-5 were collected by the

writer at the locations indicated. These tills were analyzed mechanically, using sieves corresponding in mesh and spacing to the Wentworth scale for the fraction greater than .125 mm. The smaller size fractions were determined by the pipette method of Krumbein. Standard quantitative procedure was followed for the determination of carbonates and other soluble matter. In studying the individual minerals that constitute the till, X-ray was used for the clay-size fraction and heavy mineral mounts made for the fraction between 1/8-1/16 mm. and 1/4-1/8 mm.

The data for samples V3-16 were compiled from the files of the Testing Laboratory of the Wisconsin State Highway Commission. The Bouyoucus Hydrometer method had been used in all analyses.

PETROGRAPHY

Hand Specimen

The Cary till throughout northeastern Wisconsin is a gray, sandy sediment. However, the percentage of the smaller size particles increases toward Lake Michigan (Thwaites[1]).

The Valders, or "Red Till" of Alden, is readily distinguished in the field from the Cary by its red color and much finer texture. This red color has been discussed by Alden (1918, pp. 310-324) and reviewed by Thwaites (1943, p. 137).

Laboratory Analysis

Mechanical analysis.—Samples of the two tills, after removal of fragments larger than 4 mm., were analyzed mechanically to determine their grain-size distribution. Unweathered samples were used in all analyses to eliminate the comminuting effect of post-depositional weathering, especially the clay-forming process (table 1 and fig. 2). Standard sieves conforming in mesh and spacing to the Wentworth scale were used for the particles larger than .125 mm. The samples were broken at this upper limit by "wet sieving" and the analysis of the finer particles made by the pipette method as described by Krumbein (1932, pp. 140-149). The time chart, as reproduced from Krumbein (1935) in Twenhofel and Tyler (1941, p. 37), was employed.

[1]Personal communication.

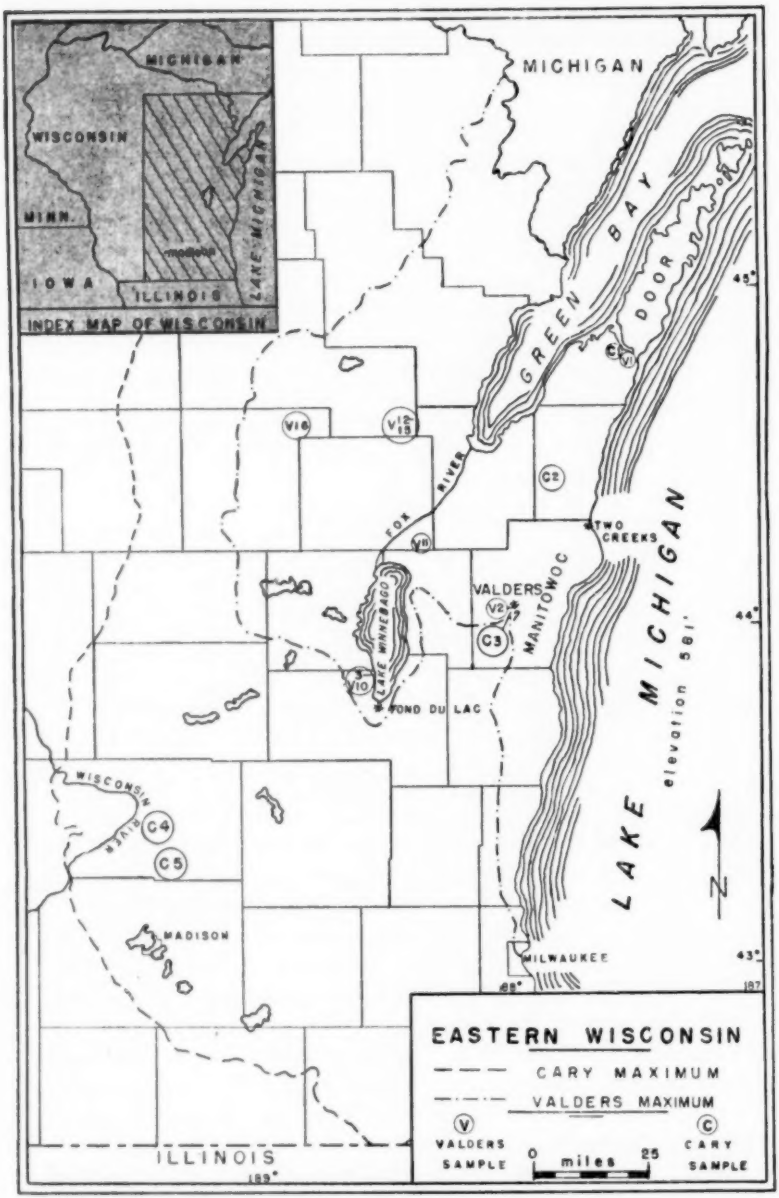

Fig. 1. Index map of eastern Wisconsin and the location of the samples studied. The location of the Cary and Valders maximum advances are after Alden (1918) and Thwaites (1943).

The size of initial sample that would yield approximately 25 grams of sediment smaller than .125 mm. was determined empirically in each case. N/100 sodium oxalate ($Na_2C_2O_4$) solution and 10-minute agitation in an electric milkshake mixer produced dispersion sufficient to prevent flocculation for more than 72 hours. The calculated weight of each fraction was expressed as a per cent of the total weight of the initial sample. Cumulative curves and statistical values were determined for the data (fig. 2 and table 1). Two separate analyses were run for each sample and an average taken in order to obtain a more accurate value and estimate the accuracy of the method and procedure.

The data, compiled by the Wisconsin Highway Commission on the grain-size distribution of possible highway materials,

TABLE 1

Statistical Values Calculated from the Grain-size Distribution of the Cary and Valders Tills

Sample	M mm.	Q_1 mm.	Q_3 mm.	QDa	So	Ska +	Clay/silt ratio
V 1	.01	.0016	.096	.047	2.45	.039	.56
V 2	.025	.0056	.12	.057	4.54	.037	.31
V 3	.023	.004	.08	.038	4.48	.019	.34
V 4	.02	.003	.17	.083	7.53	.066	.41
V 5	.035	.0066	.17	.081	5.08	.053	.34
V 6	.024	.0035	.10	.048	5.36	.028	.38
V 7	.024	.0042	.047	.021	3.32	.002	.33
V 8	.013	.0022	.055	.026	5.0	.016	.42
V 9	.024	.004	.074	.035	4.2	.015	.34
V 10	.024	.004	.100	.048	5.0	.028	.36
V 11	.038	.01	.11	.05	3.32	.022	.34
V 12	.014	.008	.03	.011	1.94	.005	.14
V 13	.05	.007	.18	.086	4.90	.043	.50
V 14	.06	.008	.22	.07	5.24	.054	.42
V 15	.023	.0053	.085	.04	4.01	.022	.44
V 16	.046	.01	.25	.12	5.0	.084	.39
C 1	.16	.07	.25	.09	1.89	.000	.15
C 2	.09	.026	.30	.137	3.36	.073	.15
C 3	.15	.04	1.01	.485	5.03	.037	.12
C 4	.23	.125	.35	.112	1.67	.007	.24
C 5	.22	.13	.40	.14	1.75	.045	.27
Valders Av.	.025	.0045	.125	.059	5.26	.040	.34
Cary Av.	.16	.065	.35	.142	2.32	.047	.17

was determined by the Bouyoucus Hydrometer method. This information was plotted as cumulative curves, and the present writer substituted the Wentworth scale for the original grade scale used.

The data compiled in table 1 and the accumulation curves presented in figure 2 show that there is a distinctive and significant difference in grain size between the analyzed samples of Cary and Valders tills. The broken center curve is the arithmetical average of the samples studied. This offers analytical and statistical evidence for the textural differences observed in the field.

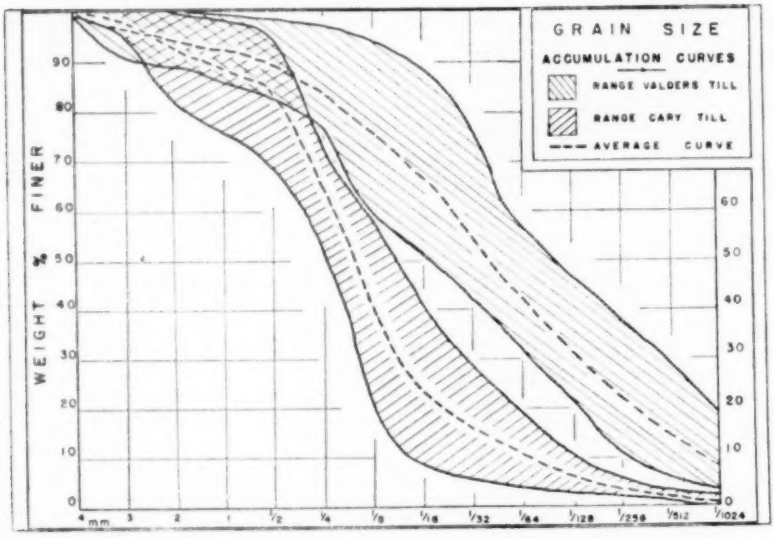

Fig. 2. Grain-size accumulation curves of the Cary and Valders tills.

Few published analyses of till are available. However, the wide range of grain size is characteristic of those reported in the literature (Krumbein, 1933; Cailleux, 1947; Horner, 1947; Deane, 1950). The Valders till from this area lacks the wide range of grain size and shows a concentration of particles in the finer sizes. This is not true of the Cary and most of the other tills reported in the literature. This fact is thought significant and is referred to again in a later section.

Soluble matter.—Carbonates and other soluble constituents in the unweathered portions of the two tills were determined by standard quantitative procedure.

Duplicate samples of each till were selected and split from the bulk sample by the method outlined by Twenhofel and Tyler (1941, p. 37). Dilute hydrochloric acid was used as the solvent and each sample was heated to 105° C. to insure the solution of all common carbonates. The weight loss was determined and expressed as a per cent of the initial sample. The results are reported in table 2.

The Valders till is slightly more calcareous than the Cary for the samples analyzed from northeastern Wisconsin. Samples of Cary till from the southern part of the state showed a much higher carbonate content due to incorporation of Paleozoic limestone and dolomite fragments. These rocks outcrop throughout eastern Wisconsin.

TABLE 2

Soluble Matter in the Cary and Valders Tills

Sample	Per cent of soluble matter by weight	
	Analysis No. 1	Analysis No. 2
Cary Till		
Sample C1	6.87	6.80
Sample C2	6.84	8.90
Sample C3	6.82	5.60
Valders Till		
Sample V1	11.15	9.34
Sample V2	9.10	9.83
Average		
Cary Till	6.97	
Valders Till	9.86	

Clay-size fraction.—The grain-size fraction 1/256 mm. and smaller, collected from each till sample, was X-rayed to determine the minerals contributing to this fraction. The pictures were taken with a copper target and nickel filter, using the small powder type camera. The results are reported in table 3.

Although there was the suggestion of the strong lines of some layered lattice minerals on the X-ray photographs, quan-

titatively they were not sufficiently strong and distinct to warrant further study. The presence of minor amounts of true clay minerals is strongly suspected. This fraction was found to consist essentially of quartz and dolomite. In the Cary till the amount of dolomite increased progressively to the south as the ice sheet moved over the Paleozoic dolomites of eastern Wisconsin. No difference was noticed among the Valders samples studied.

TABLE 3

Minerals of the Clay-size Fraction

Sample	Quantitative estimate of minerals based on X-ray	
Valders Till		
V1	Quartz (strong)	Dolomite (weak)
V2	Quartz (strong)	Dolomite (weak)
Cary Till		
C1	Quartz (strong)	Dolomite (weak)
C2	Quartz (strong)	Dolomite (intermediate)
C3	Quartz (strong)	Dolomite (strong)
C4	Quartz (strong)	Dolomite (strong)
C5	Quartz (strong)	Dolomite (strong)

Heavy mineral studies.—The grain-size fraction 1/8-1/16 mm. was treated with Bromoform (sp. gr. 2.90), and the heavy minerals separated with the aid of a centrifuge. They were then washed with acetone and mounted in Canada balsam on microscope slides. Identification was made with the petrographic microscope utilizing the mechanical stage. Difficult biaxial mineral identification was simplified by using the Universal Stage with five axes of rotation. This permitted the rapid determination of the optic sign and 2V by the methods of Berek and Dodge (Emmons, 1945). The averages reported in table 4 represent approximately 600 grains counted for each till sample. The heavy minerals of the grain-size fraction 1/4-1/8 mm. were judged to be similar after rapid examination.

The heavy mineral assemblages of the two tills in the area studied are seen to be essentially the same. The high epidote and moderately high opaque count with a strong excess of amphibole over pyroxene seem characteristic of the two tills.

Zircon and rutile were sufficiently scarce in both tills to be counted with the rare minerals. Many of the grains, especially garnet and epidote, showed strong etching. Hornblende, apatite and tourmaline appear unaffected. This etching is probably worthy of further study. Statistical analysis by the method of Student "t" distribution showed that the assumption that the two tills had different heavy mineral assemblages had a level of significance less than 2 in 100 (Jizba[2]). This is rather interesting considering the differences in age, color, texture and direction of ice movement reported in this and other papers.

Although diamonds have been reported from the Wisconsin tills (Hobbs, 1899), none was observed in the heavy mineral slides prepared for this study.

TABLE 4

Quantitative Report on the Heavy Minerals of the Grain-size Fraction 1/8-1/16 mm.

	Minerals Per cent									
Samples	Opaque	Tourmaline	Garnet	Hornblende	Epidote	Augite	Apatite	Sphene	Staurolite	Unknown and Rare Minerals
Valders Till										
V1	24	1	4	11	51	T	7	T	1	T
V2	22	1	2	13	54	2	5	1	T	T
Cary Till										
C1	29	1	2	8	56	T	3	T	1	T
C2	15	T	3	12	61	1	6	1	T	T
C3	18	1	2	15	60	1	2	–	1	T

T - trace

Microscopic examination of the tills.—The tills were examined with the petrographic and binocular microscope. The red color of the Valders till was seen to be due to clay-size particles of hematite and to hematite stain on larger grains. This color may be removed by solution in oxalic acid ($H_2C_2O_4 \cdot 2H_2O$).

[2] Zdenek Jizba, Dept. of Geology, University of Wisconsin, performed this statistical study.

Conclusions

Several facts emerge from the laboratory study. Some of these have been inferred from field studies and are here given laboratory confirmation. Granting that local minor differences may be demonstrated in both till sheets, the following conclusions seem well grounded after consideration of the petrographic data:

1. The Valders till has a considerably finer texture than the Cary.

2. The clay-size fraction of the two tills consists essentially of quartz and dolomite. The percentage of dolomite increases progressively to the south as the ice sheet moved over the Paleozoic dolomites of eastern Wisconsin.

3. The Valders till is slightly more calcareous than the Cary for the samples from the Door Peninsula. The Cary has a much higher carbonate content in the southern part of the state.

4. The red color of the Valders till may be seen under the microscope to be due to clay-size particles of hematite and to hematite stain on the larger grains.

5. The heavy mineral assemblages of the two tills are essentially the same. Many of the grains, especially garnet and epidote, show strong etching.

DISCUSSION

The Source of the Valders Till

Alden (1918) first suggested the possibility that the red, clayey till in eastern Wisconsin represented in part the lake deposits of the Michigan basin formed prior to the readvance of the ice. These deposits were removed by the advancing ice and deposited on the land as part of the till.

Thwaites (1943) gave the name Valders to this red till. In the same paper he called attention to the striking similarity between the grain-size distribution of the red till and underlying red clays of glacial Lake Chicago as seen by mechanical analysis.

The petrographic data presented in this paper offers three distinct but interrelated lines of evidence supporting the local origin of the Valders till suggested by Alden and Thwaites.

The conclusions drawn from (1) the similar heavy mineral assemblages of the two tills, (2) the higher carbonate content of the Valders till, and (3) the grain-size distribution of the two tills are subsequently discussed.

It has been demonstrated in this paper that the heavy mineral assemblages of the Cary and Valders till in the area studied are statistically identical. This similarity can be accounted for if (1) the two ice sheets had available to them similar bedrock throughout their advance, or (2) the Valders ice sheet accomplished little or no bedrock erosion and removed and redeposited a portion of the earlier Cary deposits. The first alternative appears untenable in the case of these two tills because the Valders ice followed a course decidedly to the west of that of the Cary (Thwaites, 1934). Furthermore, by its own erosion and deposition the Cary must have prepared a surface for the Valders quite unlike the one the Cary inherited from earlier glaciations. It is therefore proposed that the best possible explanation of this similarity of heavy mineral assemblages is the second advanced above. Thus it is thought that deposits of Cary age were removed and redeposited by the Valders ice. This also implies a relatively thin Valders ice sheet incapable of accomplishing extensive bedrock erosion, which is in agreement with evidence presented by Thwaites (1943).

Geographically, the immediate source area for the Valders till would be the deposits of glacial Lake Chicago, (fig. 3c). These deposits would consist largely of material dropped both directly and by bergs from the retreating Cary ice. A certain amount of land-deposited material may have been carried to the lake by streams during the Two Creeks interstadial prior to the Valders advance. If the contributing streams accomplished extensive bedrock erosion during Two Creeks time and deposited material other than the reworked Cary deposits in the lake, then the heavy mineral assemblage in the lake deposits would be modified from that of the original Cary till. The resulting Valders till assemblage would then differ from the earlier Cary. Because this is not the case, little bedrock erosion is inferred in Two Creeks time. This lack of bedrock erosion carries the implication of a Two Creeks interstadial of relatively short duration. This is in agreement with the lack of weathering profile between the two tills and other evidence reported by Thwaites (1943).

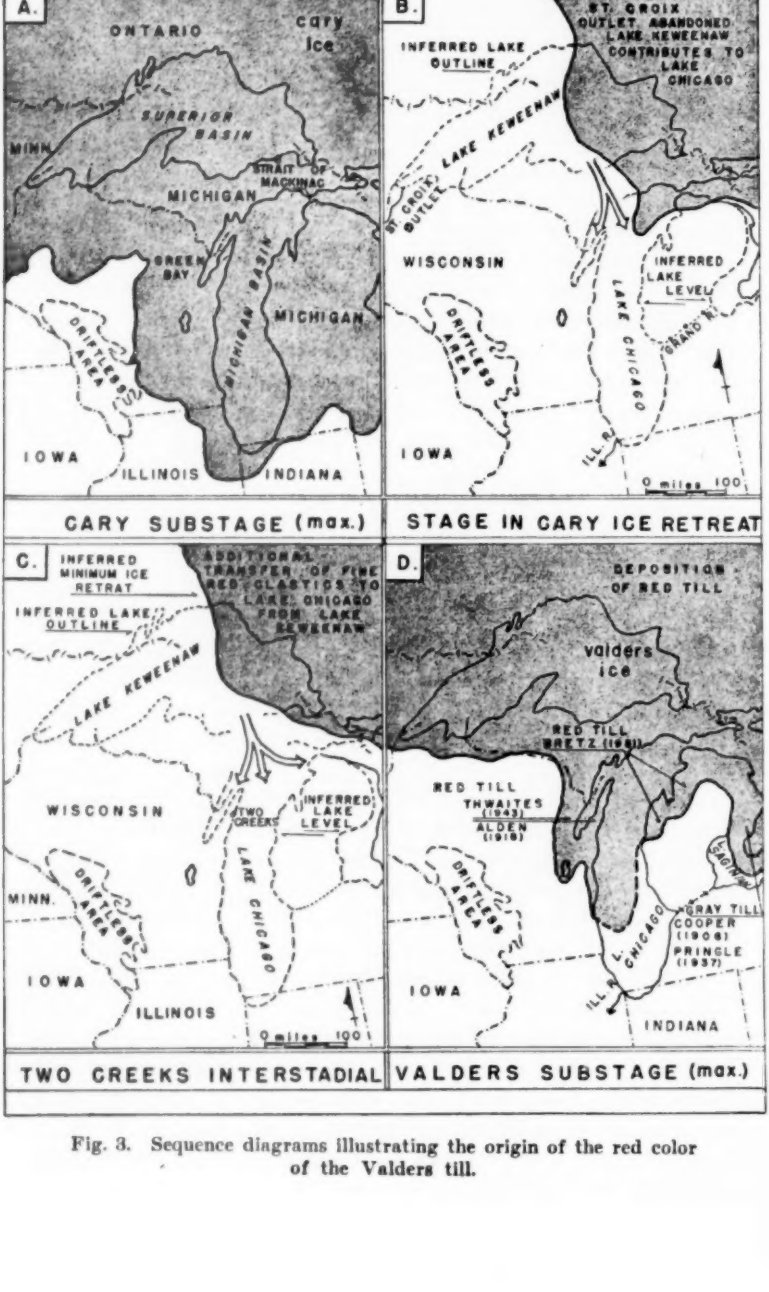

Fig. 3. Sequence diagrams illustrating the origin of the red color of the Valders till.

The Valders till from northeastern Wisconsin was found to have a higher carbonate content than the earlier Cary till. This stronger calcareous character of the Valders till in this area is thought to reflect the tendency of soft carbonate rocks to be easily comminuted. If the implications of the identical heavy mineral assemblages in the two tills are accepted, the only process which would account for the increase in carbonate content and maintain the heavy mineral assemblage is one in which there has been little addition of material. Simple mechanical reworking of Cary till by the later Valders ice would cause the reduction in particle size noticed in the Valders till but could not possibly increase its carbonate content.

It is thought that there has been a preliminary sorting of Cary deposits that were to be later reworked by the Valders ice. This sorting, if resulting in the concentration of the finer sizes, would also concentrate the carbonate minerals which, because of their softness, should be concentrated in the finer sizes. The transportation to and deposition in a lake such as glacial Lake Chicago both by bergs and by streams would accomplish such a sorting. These deposits would then be in the path of the advancing Valders ice.

The grain-size distribution curves presented previously demonstrate the fineness of the Valders till. The high degree of concentration of particles in the silt and clay range of the samples studied strongly suggested a preliminary sorting before incorporation in and deposition by the late Wisconsin (Valders) ice. This concentration of particles in the silt and clay ranges and the general scarcity of larger size fragments is highly suggestive of preliminary sorting in a lacustrine environment.

From this evidence the suggestion is again made that the Valders till in eastern Wisconsin represents deposits of Cary age deposited in glacial Lake Chicago, plus additional Cary till removed from the surrounding land in Two Creeks time and also deposited in this lake. These lake sediments were then eroded and redeposited on the land as till to record the Valders glaciation.

Origin of Red Color of Valders Till

The most striking characteristic of the Valders till is its strong red color. It is primarily on this criterion that the two tills are separated in northeastern Wisconsin. This method is

not applicable south of Lake Superior in northwestern Wisconsin and northeastern Minnesota where both ice sheets traveled over the red sandstones and shales of Keweenawan age and where both tills carry a high percentage of these red rocks (fig. 4). The Valders till is also reported to be red in the northern and northwestern parts of lower Michigan (Leverett and Taylor, 1915; Bretz, 1951). It is lacking in eastern Michigan, (Cooper, 1905; Pringle, 1937).

The local source of the Valders till discussed earlier excludes the possibility that the red color was acquired by the till through

Fig. 4. The distribution of red sedimentary rocks in the Lake Superior region (modified from Leith, 1935). The sub-lake contacts have been inferred from the sub-lake topography by F. T. Thwaites.

bedrock erosion in the Lake Superior Region. This is thought the case despite the fact that the Valders ice followed a course to the west of the Cary and would thus have had available to it a greater outcrop area of the red rocks (fig. 4).

The color is seen under the microscope to result from fragments of hematite in the clay size range and to a fine stain on the larger grains. Alden (1918) noticed this. At the suggestion

of Chamberlin, he proposed that the red color recorded the movement of silt and clay-size fragments of the red sandstones and shales of the Lake Superior region from the Superior basin to the Green Bay trough and Lake Michigan basin during retreat of the earlier (Cary) ice. The readvance of the ice picked up and redeposited these red sediments to give the distinctive color to the till of the later (Valders) glaciation.

In view of our present knowledge this appears to be the correct explanation. Heavy mineral studies, limited to the range of coarse silt-fine sand, would not detect a minor change in the clay size fractions. Thus the addition of clay-size material from the Lake Superior basin to glacial Lake Chicago would not alter the heavy mineral assemblage as recorded in the range from 1/4-1/16 mm. The present data supports, in general, the views of Alden and Chamberlin.

Cary ice, on retreating from its maximum position of advance (fig. 3a) formed a lake in the Superior basin. This lake, here named glacial Lake Keweenaw for the Keweenaw Peninsula of Upper Michigan, probably drained in its early stages via the St. Croix river as did later glacial Lake Duluth (Leverett and Taylor, 1915) on retreat of the later Valders ice. Applying the name glacial Lake Duluth to the water body held in the Lake Superior basin by the Cary ice would be incorrect because this early lake was completely destroyed during the Late Wisconsin (Valders) glaciation. As the Cary ice retreated and Lake Keweenaw grew in size, a water connection must have been formed between it and glacial Lake Chicago to the south across Upper Michigan (fig. 3b). It is proposed that the fine sediments produced by glacial erosion in the Lake Superior basin, which is underlain predominantly by the red sedimentary rocks of Keweenawen age, would in part be carried through to Lake Chicago. The outlet to the west would be abandoned at this stage.

It is strongly suspected that the water connection between the two lakes, Keweenaw and Chicago, was one of moderate gradient. This is inferred from the necessity of transporting only fine silt and clay-size fractions to the exclusion of the larger sizes which would alter the heavy mineral assemblages in glacial Lake Chicago. The heavy mineral studies being confined to the range of fine sand would not detect changes in the very fine sizes.

Wilson (1932) showed that the forest bed at Two Creeks, which rests on red lacustrine varved clay of glacial Lake Chicago, required a minimum retreat of the Cary ice north of the Straits of Mackinac. This retreat resulted in the opening of this outlet to the east and the partial draining of Lake Chicago. It was at this low stand of the lake (Bowmanville level of Baker, 1920; Bretz, 1951) that the forest bed was formed. This is the maximum known retreat of the Cary ice (fig. 3c).

Red till has been reported from the Lake Michigan shore of Lower Michigan, (fig. 3d). It is apparently lacking to the east on the Lake Huron shore. Thus it is thought that the advance of the Valders ice witnessed the erosion of these lake sediments, deposited during the pre-Valders stages of Lake Chicago. These deposits were predominantly reworked Cary deposits plus the additional fine red sediments from Lake Keweenaw. This commingled material would then be deposited by the Valders ice on the land areas surrounding the Lake Michigan basin. It is on these land areas that the red till is reported.

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ESSAY REVIEWS

Principles of Regional Geology of Continents. Vol. 1, Europe, Asia, North America; by A. N. MAZAROVICH. 347 pp., illus. (in Russian). Moscow, 1951 (University of Moscow, USSR).—The author, who died recently, was professor of geology at the University of Moscow. Earlier he published two very fine textbooks on "Historical Geology" and "Principles of Geology of the USSR," as well as over a hundred papers on various subjects in geology. His principal interest was in Permian rocks and especially in tectonics of the Earth's crust and the development of geosynclines.

The present book is published posthumously and will be followed by the second volume under the same title dealing with regional geology of South America, Africa and Australia and the geological structure of the oceans. It will include also the author's summary of the evolution of the structure of the earth's crust as a whole.

The author states in the introduction that these two volumes do not pretend to be a monograph. It is a textbook based on his lectures on regional geology of the World given in 1947-1948 and the principal monographs on general stratigraphy and tectonics of various parts of the World. Other literature is used very little. The list of literature at the end of the first volume consists of fewer than a hundred titles, although it does not include numerous other sources, to which references are made in the text.

Regional geology of Europe is outlined in seven chapters (pp. 15-152). These are: 1. General characteristics of the continent; 2. Russian Platform; 3. Caledonian folded belt of northwestern Europe; 4. Hercynian folded structure; 5. Alpine folded belt; 6. Synthesis of Europe, and 7. Ores and other useful resources. The next part (pp. 153-240) deals with Asia and is divided into nine chapters, as follows: 1. General characteristics of the continent; 2. Siberian Platform; 3. Ural-Tian-Shan folded structure; 4. Verkhoyansk - Khingan folded structure; 5. Sino-Tibet folded region; 6. Himalayan Alpine folded belt; 7. East-Asiatic geosyncline; 8. Synthesis of Asia, and 9. Ores and other useful resources. The last part (pp. 241-305) is devoted to the geology of North America and consists of eight chapters: 1. General characteristics of the continent; 2. North American Platform; 3. Arctic and East Greenland folded belts; 4. Appalachian folded belt; 5. Cordilleras; 6. Mexico, Central America and West Indies; 7. Synthesis of North America, and 8. Ores and other useful resources.

Practically all chapters dealing with individual regions are subdivided into five sections each. These sections are as follows: 1. General outline of the region; 2. Stratigraphy of the Precambrian basement; 3. Stratigraphy of Paleozoic strata; 4. Stratigraphy of

Mesozoic and Cenozoic strata, and 5. Tectonics. The three chapters, one in each part of the book, devoted to what the author refers to as synthesis of individual continents, consist of similar sections, such as: 1. Formation of the Precambrian Platforms or massives; 2. Caledonian (Lower Paleozoic) foldings; 3. Hercynian (Upper Paleozoic) foldings; 4. Alpine (Cenozoic) foldings, and 5. Summary and conclusions. Beside these, other sections are devoted to various peculiar features of individual continents, for example, Formation and development of Alpine geosyncline in Europe; Yenshan (Mesozoic) folding and formation of Mesozoic Platform in Asia, and Mesozoic downwarping and Yenshan folding in North America.

The text is illustrated by schematic diagrams and columnar sections. At the end of the text is an appendix including 86 one-page paleogeographic and tectonic schematic maps. Twelve of these maps represent the essential features or "paleogeography" of North America in various periods from Proterozoic to Pliocene. In addition to these schemes at the end of each part of the book there is a roughly schematic tectonic map of the respective continent.

In the introduction to the discussion of geology of North America Mazarovich makes several statements and remarks which may be of interest to American geologists. The following is a free translation of the passage under the subtitle: peculiarities of American school of geology (pp. 244-45).

"Geology in American is characterized by a series of peculiarities in which it sharply differs from the European school. The position of America between the two oceans strongly influenced the trend of thinking of American geologists. The theory of eternity of oceanic depresssions is more popular in America than in any other country. All American paleographic and tectonic schemes, of which one should mention those of Shuchert, Willis and Grabau, are based on this assumption.

"America is the fatherland of the theory of geosynclines suggested in the forties of the last century by Dana and J. Hall who stated that geosynclines are formed between the continents and the oceans. After it had been established that deposits of which the Appalachians and Cordilleras are built included material that had been brought from the side of the ocean, Grabau, Shuchert and their followers introduced the concept of 'Borderlands' separating the geosynclines from the ocean. This concept is the product of wishful thinking and is unacceptable to us. American geologists needed it for explanation of certain peculiarities in the structure of the Appalachians and Cordilleras, although it is not based on any geological evidence. American geologists introduce this entirely abstract concept merely because it follows from the theory of

eternity of oceanic depressions. As a matter of fact, such 'Borderlands' represent anticlinoria in the geosynclinal belts.

"The science of stratigraphy is being developed in America on principles that are fundamentally different from those employed by the European stratigraphers. This has happened because the stratigraphy as conceived in the European school has been established upon subdivision of geological deposits on the basis of paleontological records, whereas American stratigraphers have started the geological survey of their country with the identification of lithologic formations which were identified in the course of searches for coal, mineral oil and various ores. It has led to the recognition of a great many local 'suites.' Paleontologic study of the latter in America lagged very considerably behind their establishment.

"In the United States it is customary to divide systems into series which do not correspond to our divisions and are differentiated on the evidence of old erosion surfaces and unconformities. Series are further divided into groups and the latter into formations which are identified on lithologic principles. A formation of American stratigraphers is a definite complex of sediments more or less corresponding to our suite. Each formation is given a geographical name. Formations are not determined by the paleontologic nature of rocks and do not possess characteristics which would indicate their age. Moreover, a different nomenclature of sediments is used in different States. Formations, in turn, are subdivided into more narrowly defined units, some of the most conspicuous of which also are given their own proper names.

"As a result of such a system in the United States many thousands (more than 13,000) of stratigraphic names are recognized which are unrelated to one another. Therefore, it is extremely difficult to make use of American literature. Recently, attempts to systematize the general stratigraphy have been made (Shimer, 1934; Reeside, 1933, and others). Nor has a rounded picture of tectonics been achieved, hence, it is very difficult to gather a general picture of geology of North America. European geologists who are interested in geology of the American continent began to analyze this structure by their own methods. One may mention works of Stille, Ruedemann, Waterschoot van der Gracht as well as those of Uspenski and Shatski, which allow one to comprehend the basic data on geology of America."

C. C. NIKIFOROFF

Principles of Geology; by JAMES GILLULY, AARON C. WATERS, and A. O. WOODFORD. Illustrated by ROBERT R. COMPTON. Pp. vi, 631; 296 figs.; 16 tables. San Francisco, 1951 (W. H. Freeman & Co., $5.75).—This is not just another textbook of elementary geology but, as stated in the preface, it is one which attempts to go behind the facts and stress the "analysis of processes," the "kind of evidence on which geological conclusions are based," and the "sequence of reasoning that is used in the historical development of the subject." These aims have been carried out within the individual sections of the book and on the whole there has been a subordination of technical terminology to the discussion of ideas and concepts. The publishers have obviously cooperated with the authors in producing a book in which both the printing and the reproduction of illustrations are clear and of good workmanship. We have not made the traditional search for printer's errors.

The authors are to be congratulated on the number, variety, and clarity of their illustrations. To a very large extent these have been selected from the most modern material available. Mr. Compton's line drawings are simple, intelligible, and forceful, the happy result of imagination and good draftsmanship. They also represent eighteen different types of geologic illustration, almost every type with which the average undergraduate will have to deal.

The examples used as illustrations in this book are somewhat cosmopolitan, with cases selected from many parts of the world. This will undoubtedly be welcomed by many geologists who are strongly conscious of the universal nature of their subject, although it is not as certain that American college students will appreciate the point since many of the examples cited have little connection with the student's personal experience. Regardless of this, the underlying aim is educationally desirable.

The authors obviously join us in favoring an educational objective which is already being approached in some colleges, namely, that of deliberately increasing the general educational value of the introductory course by explaining many phases of physical geology in terms of the principles of physics, chemistry, mathematics (statistical analysis), and other subjects. In this text, for example, Chapter 4 introduces the student to a considerable amount of crystal chemistry and related concepts in connection with the study of minerals, while Chapter 3 and parts of Chapter 18 describe and apply some of the fundamental principles of physics. The use of statistics in graphs and charts, as well as the discussion of the quantitative aspects of many processes, is evident throughout the book. The authors do not, however, make as deliberate use of these as does R. M. Garrels in his recent textbook covering some-

what the same field. Another corollary subject, that of world geography, is also introduced on an appreciable scale.

The authors have adopted a more mature approach in handling the details of the subject than will be found in the average textbook. This is certainly not a book which can be memorized by the student and handed back verbatim, but is rather one that requires considerable mental effort on his part. Because of this the instructor may well be forced to do more constructive teaching in helping the students to obtain a full appreciation of the subject matter. In other words the use of this book as a text may very well raise the minimum standard of a course, although it will not necessarily affect the other end of the scale.

Teachers will find in particular that such discussions as those on X-ray diffraction patterns (pp. 60-61), the Bowen reaction series (pp. 461-463), and Darcy's Law (pp. 334-335) are somewhat above the level of material usually included in an elementary textbook.

The deliberate use of the "historical approach" will be more appreciated by mature geologists than by beginning students, for our experience shows that a considerable and comprehensive knowledge of present-day concepts is necessary before one can appreciate the trials and errors of the past. We feel that this approach is much more effective at a higher educational level and that at the beginning level it should be used with caution and with recognition of possible confusion of the student.

Probably not enough thought has been given by geologists to the advantages of the deductive approach to the teaching of elementary courses. We believe that often much time and confusion can be saved by leading the beginning student from the general theory to the particular observation. On the other hand, in the case of advanced students the operation should be completely reversed. Thus, to take a specific example, a beginner usually obtains a better grasp of igneous rocks *in the time available* if he considers our present knowledge of igneous processes *first* and then follows this by a study of the rocks themselves. This is in direct contrast to the actual line of inductive reasoning by which our theories of igneous processes have been reached. On educational grounds, therefore, we find it difficult to approve the early consideration of the igneous rocks on pages 74 to 87, well separated from and preceding the discussion of igneous activity on pages 436 to 467. By the same argument, the discussion of the realms of marine sedimentation (pp. 406-427) coming over three hundred pages *after* the description of sedimentary rocks (pp. 69-74) seems difficult to justify.

The above criticism is based on our experience that students are less confused and develop a clearer perspective if the teaching of physical geology is based as far as possible on a chain of topics

related to each other as they actually are in nature, e.g., earth's interior→igneous activity→igneous rocks→weathering (chiefly of igneous rocks)→erosion and deposition→sedimentary rocks→deformation (of sedimentary rocks), etc. Some textbooks are flexible enough so that the order in which the material is considered can be changed to fit one's own ideas, but we feel that this book is so thoroughly integrated that its order cannot be rearranged without losing more than is gained.

It has also been our personal experience in teaching elementary geology that the first few subjects introduced during the course should be concerned with some phases of geology with which the student is already somewhat acquainted and in which he can be immediately interested. In other words a problem of applied psychology is involved. We do not feel that the first fifty pages of this book dealing with the figure of the earth, first order topographic features, gravity, isostasy, and the strength of materials are likely to attain the goal advocated above.

In one particular this text differs from many others. Disciples of William Morris Davis and C. A. Cotton will search almost in vain for mention of geomorphic cycles. These are given scant or very indirect treatment. The discussion of the evolution of a stream valley (pp. 264-265 and fig. 12-13) treats the cycle in an incidental fashion while the section on shorelines (pp. 402-405) brings in the idea very indirectly. The authors give us the impression that they consider the classic concept of cycles to be such a theoretical ideal that the student is likely to be misled by it in his study of actual cases.

We feel that this book is an important contribution to the teaching of elementary geology because it represents a very real attempt to raise the intellectual level of the subject, because it introduces considerable new material not formerly included in general textbooks, and because the authors have presented most of their discussions, explanations, and illustrations in a clear and stimulating fashion. Our chief criticism concerns the sequence in which the separate topics are developed. This is not surprising since it is in this area that the greatest differences of personal opinion are likely to appear. Considering the highly individualistic nature of most geologists, it is improbable that they will ever agree on what is the best psychological approach to be used in teaching their subject.

Finally, whether or not one is in agreement with the plan of presentation used in this text, the book should stimulate a considerable re-examination of teaching methods and their guiding principles. This, in itself, is ample justification for the existence of the book.

ELWYN L. PERRY
FREEMAN FOOTE

REVIEWS

Physical Properties and Analysis of Heavy Water; by I. KIRSHENBAUM. Pp. xvi, 438. New York, 1951 (McGraw-Hill Book Company, Inc., $5.25).—This comprehensive monograph is Volume 4A of Division III of the National Nuclear Energy Series. It contains a well organized, critical survey of the research work carried out under the Manhattan Project in the period 1941-1945 as well as the published literature up to 1945 on the physical properties and analysis of heavy water.

The book is divided into six chapters. The first two chapters contain a comprehensive summary of all the important physical properties and equilibrium constants for exchange reactions of heavy water enriched either in deuterium or in O^{18}. Water enriched in tritium is not discussed in this book. Chapter 3 and Chapter 4 contain an authoritative discussion on the construction, operation and limits of accuracy of the mass-spectrometer for the isotopic analysis of heavy water. The decomposition of water sample by electrolysis, by hot tungsten filament, and by reaction with zinc, and the equilibration of water with hydrogen or carbon dioxide for mass-spectrometric analysis are thoroughly discussed. Chapter 5 contains a description of the other methods of isotopic analysis of heavy water. The various modifications of the float method are discussed in great detail. The falling drop method is described. The gradient tube and several other optical and thermal methods are also briefly reviewed. The last chapter contains a summary of the literature on the natural abundance of deuterium and heavy oxygen up to 1945. The data on the variation of deuterium content of different natural waters may be of particular interest to those concerned with the terrestrial isotopic distributions.

The beginner as well as the expert in research with isotopic tracers will find "Physical Properties and Analysis of Heavy Water" a useful tool in their work for many years to come.

JUI H. WANG

Elements of Ceramics; by F. H. NORTON. Pp. xiv, 246; 208 figs., 75 tables. Cambridge, Mass., 1952 (Addison-Wesley Press, Inc., $6.50).—Ceramics is one of the oldest professions known to man and yet it has been one of the last fields to benefit from modern technology. The industry itself is somewhat to blame for this, since it seems rather reluctant to modify traditional practices of long standing. For instance, feldspar and quartz are separated by hand-picking at the pegmatite mines and then remixed in various proportions at the ceramic plants. But, in graphic-granite(runite), potash feldspar and quartz occur in large deposits already inter-

mixed in a remarkably constant ratio. It seems quite possible that this material might easily be mined in large quantity and used in the industry, at less cost, along with small additions of quartz or feldspar as needed.

Professor Norton has done much to explain or remove many of the "old wives' tales" and senseless traditions of the ceramic industry. He has done so by examining the various practices and processes of the industry in the light of sound scientific principles. His text is a compilation of principles, hypotheses, and processes which are fundamental to a proper understanding of the behavior of plastic masses. For instance, figure 3-1 is merely a histogram of particle size distribution of various natural clays. This is, however, basic information needed to explain the important characteristics of different raw clays, such as plasticity, dry strength, and base exchange capacity. Yet, such graphs are almost non-existent. Professor Norton himself states that "there is no publication in which the properties of ceramic clays have been adequately treated." Fortunately, his text will do much to remedy this situation.

The subject matter is arranged in logical order beginning with discussions on the origin, occurrence, and properties of the raw materials. This is followed by chapters on the physico-chemical reactions and properties of the plastic masses throughout the various stages of mixing, forming, drying, firing, glazing, and decorating. Emphasis is placed on the basic principles underlying the various processes rather than on the finished ware. The text is illustrated with excellent line drawings, tables, photographs, and an abundance of graphs, almost all of which were prepared by the author to accompany the text.

It is unfortunate, however, that Professor Norton has made so many geologic errors. The geologic time chart contains numerous errors and is certainly outdated (it lists the Neopaleozoic and Eopaleozoic Eras and also the Comanchean Period). Mineralogically, besides including spodumene as a feldspar, the author states, "quartz occurs as an important constituent of some igneous rocks such as granite, *syentite*, . . ." (italics mine). These errors may, of course, seem insignificant to non-geologists, but it is hoped that they will be corrected in later editions.

On the other hand, praise and thanks should be extended to Professor Norton for his ability in communicating a visual understanding of the structure of the clay minerals. The too-familiar two-dimensional "network" drawings have not been merely reproduced; instead, the individual layers have been separated from the close-packed structure with the result that the structure should now be obvious to anyone with eyesight.

Professor Norton has earned the gratitude of all ceramists, whether they be specialists in the industry, students, or laymen interested in ceramics only as a hobby. MEAD LEROY JENSEN

Out of the Sky, an Introduction to Meteorites; by H. H. NININGER, Pp. viii, 336; 22 figs., 52 plates. Denver, 1952 (University of Denver Press, $5.00).—Mr. Nininger has collected in this volume accounts of most of the features of meteoritic material and most of the phenomena attendant upon the fall of such material. The account is simply written with a pleasing style that should readily achieve the expressed purpose of serving "first . . . those persons who read popular science out of sincere curiosity about the physical universe." The second purpose, to serve students of science (and of specific sciences), is also fulfilled at elementary levels. It is unlikely that the book will achieve wide recognition as an advanced textbook.

Thirty-three chapters recount many specific examples of meteorite falls, a description and classification of known types of meteorites, the author's experiences in assembling a notable meteorite collection, and speculations as to the origin and meaning of various meteorite structures. The last chapter is a plea for the establishment of a national institute of meteoritics under the Federal Government. A 5-page bibliography of publications by H. H. Nininger, and a 13-page index complete the book.

The chapter on meteoritic craters does not include reference to the work of Baldwin in which dimensions of meteorite craters, shell-holes, and even the craters of the moon, are shown to form a coherent group.

This book is heartily recommended for wide distribution; it should stimulate much interest, and many will find it a useful reference.

HORACE WINCHELL

Cosmology; by E. FINLAY-FREUNDLICH. International Encyclopedia of Unified Science, Vol. 1, No. 8. Pp. iii, 59. Chicago, 1951 (University of Chicago Press, $1.25. paper cover).—This is an admirable review, in 60 pages, of the observational background and the relativistic treatment of the cosmological problem, on the level of a first-year graduate student. Even an undergraduate who has mastered the basic concepts of the tensor calculus will read it with profit. And the teacher of elementary courses in astronomy will find much that is useful to him. It is strange, however, that Professor Freundlich has not taken any notice of the developments since 1935, except for a few references in the bibliography. This is particularly to be regretted in view of the great skill with which he has sketched the earlier phases. RUPERT WILDT

Geologic Maps of 14 Quadrangles in Gillespie County, Texas; by VIRGIL E. BARNES. Geologic Quadrangle Map Series, Bureau of Economic Geology, Austin, Texas, 1952 (University of Texas, 75¢ each).—The Bureau of Economic Geology of the State of Texas has initiated a new series of geologic maps which, like the maps of the series started a few years ago by the U. S. Geological Survey, are accompanied by no more text than can be printed opposite the map on the other half of the folded sheet. Thus is reinforced once more the post-war trend for official agencies to publish maps and charts with relatively little text, as a means of making information quickly available while the full reports pass slowly through the editorial mills.

The 14 maps that lead off the present series are the work of Virgil E. Barnes, and they cover a large part of Gillespie County, which lies along the northern margin of the Edwards Plateau near its eastern end. The base maps are on a scale of 1:31,600, but they show no topography. The larger part of the area mapped is underlain by practically horizontal Lower Cretaceous rocks (Trinity and Fredericksburg stages; Fredericksburg is the county seat of the county). The northern edge of the county includes part of the southern edge of the Llano-Burnet uplift, exposing Precambrian metamorphic and igneous rocks and Upper Cambrian and Lower Ordovician sedimentary rocks, somewhat faulted; these rocks also appear farther south as inliers. The texts describe these formations and mention the mineral resources of the map areas (chiefly construction materials and ground water). Detailed stratigraphic sections and well logs are given beneath some of the texts—an excellent innovation. The maps are folded into 9 by 10¼ inch manila covers.

The rapidly growing number of new map and chart series issued by various organizations poses difficult problems for custodians of geological libraries, who must keep track of them all and provide space for them, despite their odd sizes. The lack of serial numbers in this series and the comparable U. S. Geological Survey series compounds the difficulty of insuring complete sets. It is to be hoped that the issuers of such series will take special care to see that potential depositories are kept fully informed of what maps have been issued, by periodical index maps or other means. But such bibliographic doubts do not lessen the great value of these new maps in the campaign to complete the geologic mapping of the country.

JOHN RODGERS

The Growth of Physical Science, 2d ed.; by SIR JAMES JEANS. Pp. x, 364; figs. and plates. London and New York, 1951 (Cambridge University Press, $3.75).—It is a distinct pleasure to pick up a survey of so broad a field as the history of the physical sciences

and find neither a monotonous recitation of names, dates, and contributions nor a monumental multiple-volume work filled with inconsequential trivia supplied by over-conscientious biographers.

The author's well known literary style is displayed at its best. Only a fine scientist and a master of exposition could hope to crowd the essential material into so few pages and still produce a volume which is comprehensible to a reader without mathematical or technical background.

The book traces the growth of the physical sciences, including astronomy, from their first beginnings in Greek mathematics to the modern quantum theory. The reader is assumed to be without scientific training, but this does not mean that the book will not also serve the student as an excellent general survey before undertaking one of the more comprehensive histories of a particular period or subject.

A reader familiar with a particular period might well feel that the discussion of that phase is somewhat sketchy, but he would be the first to agree that all of the major schools and lines of development are adequately discussed, and that some detail must be omitted.

In each section the author has treated in greater detail the contributions and life of one or more individuals. No doubt this was intended to break the monotony of recitation and to give some insight into the scientific maturity of the period. Such a procedure, while interesting to the reader, does have a tendency to break into the line of thought.

The author has attempted to carry his work practically up to the publication date of the book. This is reasonable if one has space to do justice to the current rapid expansion of science. Unfortunately in this case it leads to a rather thin skim over current work, leaving only the broadest outline of modern science. At a time when modern developments are attracting so much public interest, a more complete discussion might well be appropriate.

As a second edition the book has been corrected for misprints, and revised by Mr. P. L. Grant of the Cavendish Laboratory in the light of the latest research on the subjects with which it deals.

D. E. HARRISON, JR.

PUBLICATIONS RECENTLY RECEIVED

The Concealed Coalfield of Yorkshire and Nottinghamshire, 3d ed.; by W. Edwards. London, 1951 (Geological Survey of Great Britain, Dept. of Scentific and Industrial Research. His Majesty's Stationery Office, £1 2*s*. 6*d*).

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Man and His Biological World, revised ed.; by F. C. Jean, E. C. Harrah, F. L. Herman, and S. R. Powers. New York, 1952 (Ginn and Company, $5.00).

Vinyl and Related Polymers; by Calvin E. Schildknecht. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $12.50).

Russia's Lomonosov, Chemist, Courtier, Physicist, Poet; by Boris N. Menshutkin. Princeton, New Jersey, 1952 (Princeton University Press, $4.00).

The Exact Sciences in Antiquity; by O. Neugebauer. Princeton, New Jersey, 1952 (Princeton University Press, $5.00).

Aspects of Form; by Lancelot Law Whyte. New York, 1951 (Pellegrini & Cudahy, $6.00).

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VOL. 251 No. 2, 1953

CONTENTS

THE EFFECTS OF EXTRUSION AND SOME OTHER PROCESSES ON THE MICRO-STRUCTURE OF CLAY
J. H. Weymouth and *W. O. Williamson* 89

SHORELINES OF THE GLACIAL GREAT LAKES IN COOK COUNTY, MINNESOTA ..... *Robert P. Sharp* 109

THE PETROLOGY OF THE CARY AND VALDERS TILLS OF NORTHEASTERN WISCONSIN ..... *Raymond C. Murray* 140

ESSAY REVIEWS

Regional Geology of Continents; by A. N. MAZAROVICH ... *C. C. Nikiforoff* 156

Principles of Geology; by JAMES GILLULY, AARON C. WATERS, and A. O. WOODFORD ..... *Elwyn L. Perry* and *Freeman Foote* 159

REVIEWS

Physical Properties and Analysis of Heavy Water; by I. KIRSHENBAUM *Jui H. Wang* 162

Elements of Ceramics; by F. H. NORTON ..... *Mead Leroy Jensen* 162

Out of the Sky, an Introduction to Meteorites; by H. H. NININGER *Horace Winchell* 164

Cosmology; by E. FINLAY-FREUNDLICH ..... *Rupert Wildt* 164

Geologic Maps of 14 Quadrangles in Gillespie County, Texas; by VIRGIL E. BARNES ..... *John Rodgers* 165

The Growth of Physical Science, 2d ed.; by SIR JAMES JEANS *D. E. Harrison, Jr.* 165

PUBLICATIONS RECENTLY RECEIVED 167

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